US Army Corps of Engineers
Waterways Experiment Station

Final Report
CPAR-SL-98-5
September 1998

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Unique Polymeric Fiber and Fiber Delivery Systems for the Economic Preparation of High-Fiber Content Concrete with Superior Physical Properties

by

Billy D. Neeley, Donna C. Day, James E. Shoenberger

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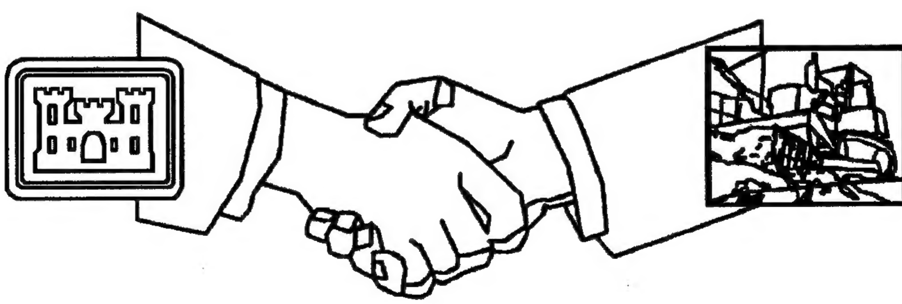

A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

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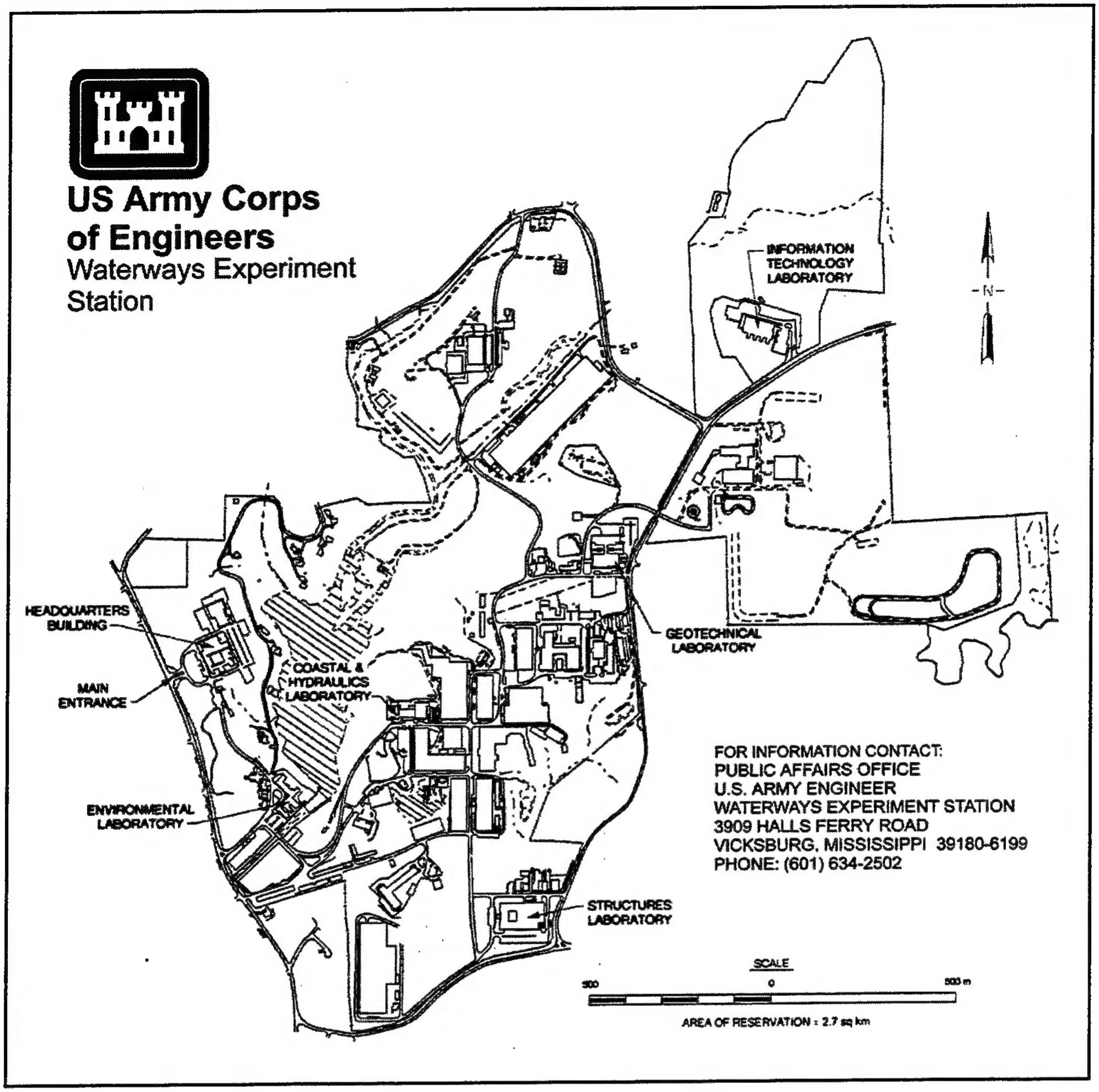

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Preface

The investigation described in this report was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), by the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), in cooperation with the 3M Company, St. Paul, MN. This cooperative research and development agreement was a part of the Construction Productivity Advancement Research (CPAR) Program. The HQUSACE Technical Monitors were Messrs. Daniel Chen and Greg Hughes (CEMP-ET).

Separate efforts were performed by WES and the 3M Company to meet the study objectives. Experiments conducted at WES were under the general supervision of Messrs. Bryant Mather, Director, SL; John Q. Ehrgott, Assistant Director, SL; William F. McCleese, CPAR point of contact at WES; and Dr. Paul F. Mlakar, Chief, Concrete and Materials Division (CMD), SL. Direct supervision was provided by Mr. Edward F. O'Neil, Acting Chief, Engineering Mechanics Branch (EMB), CMD, SL. Mr. O'Neil and Mr. Billy D. Neeley, EMB, were the Principal Investigators. Messrs. Brian H. Green, Michael K. Lloyd, Jimmy W. Hall III, Dan E. Wilson, R. Cliff Gill, Joe G. Tom, Michael Hedrick, and Rudy Andreatta, and Mses. Donna C. Day and Bobbylin Gurrerro, EMB, assisted in preparing and testing the concrete mixtures. Messrs. James Shoenberger, Webb Mason, and Dennis Matthews, Pavement Systems Division (PSD), Geotechnical Laboratory (GL), and Dr. Michael I. Hammons, formerly of PSD, GL, assisted in the design and analysis of the whitetopping demonstration project. The engineering support and commercialization effort of the 3M Company were the direct responsibility of Mr. Clifford N. MacDonald, Technical Services Specialist, New Products Department (NPD). General supervision was provided by Mr. A. Brian Doran, Director, NPD. Dr. V. Ramakrishnan, Distinguished Professor of Civil Engineering, South Dakota School of Mines and Technology, was a consultant to 3M and provided valuable insight during the execution of this research project. Messrs. Alfred B. Crawley, Research Department, Mississippi Department of Transportation, and J. Michael Pepper, Assistant Director, Mississippi Concrete Industries Association, were instrumental in the planning and execution of the whitetopping demonstration project. This report was prepared by Mr. Neeley, Ms. Day, and Mr. Shoenberger.

Permission to use the copyrighted material in Appendix D of this report was obtained from the 3M Company.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

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1 Introduction

Background

General

Concrete is a very popular and competent construction material. It can have high compressive strengths and be durable for many years, while being relatively inexpensive compared with other materials used in construction. While its good qualities are used to advantage during design of a structure, there are also limitations that must be considered. Concrete has two significant deficiencies, low tensile strength and low tensile-strain capacity. Numerous microcracks commonly found in concrete propagate rapidly under applied stress. Once the tensile stress induces a tensile strain that exceeds the tensile-strain capacity of the concrete, the microcracks become macrocracks, and ultimate failure occurs soon thereafter. In many design codes, the tensile strength is simply ignored or assumed to be zero when the properties of the concrete are considered. These deficiencies have led to considerable research in an effort to develop new approaches to improve the tensile properties of concrete and lessen its brittleness. Much of this research has centered around incorporation of various types and quantities of fibers into the concrete matrix. Committee 116 of the American Concrete Institute (ACI) defines fiber-reinforced concrete (FRC) as "concrete containing dispersed, randomly oriented fibers" (ACI 1995a). Fibers of various natural materials have been used to reinforce brittle materials since ancient time. Several research efforts into FRC were initiated in the 1950's, and research efforts have intensified in recent years. ACI Committee 544 (ACI 1995b) discusses much of this research. A five-volume bibliography was published by the U.S. Army Engineer Waterways Experiment Station (USAEWES) between 1976 and 1982 (Hoff, Fontenot, and Tom 1976, 1977, 1979, 1980, 1982). This bibliography provided 1,913 references. An additional bibliography on FRC is provided in Appendix A, listing a body of research from 1964 through 1997.

The structural load-carrying capacity of FRC has always been an issue in civil engineering communities. The ability of the fibers to carry tensile load after the concrete has cracked is generally at the center of such discussions. While fibers cannot be used to replace steel reinforcing bars in the design of a

structural element to resist bending, i.e., moment loading, they have proven themselves capable of reducing shrinkage cracking, improving flexural toughness and impact resistance, and keeping the width of tensile cracks small, thereby improving the appearance and durability of the concrete.

Fiber types: benefits and limitations

A variety of fiber materials in various shapes and sizes has been developed for use in FRC and is commercially available to the construction industry. Steel and polymeric fibers are most commonly used and will be discussed in more detail in the following paragraphs. Glass, carbon, and various types of natural fibers have also been used, but to a lesser extent. In addition to material type, size, and shape, a numerical parameter called aspect ratio is commonly used to describe a fiber. The aspect ratio is defined as the fiber length divided by its diameter (or equivalent diameter in the case of non-round fibers). Typical aspect ratios range from 30 to 150 for steel fibers having lengths from 6.0 to 76.0 mm (0.25 to 3.00 in.). Fibers with higher aspect ratios can be more difficult to disperse during mixing, yet higher aspect ratios are generally considered to provide better performance in hardened concrete. However, many other factors can be equally or more important in determining ultimate performance. As will be subsequently discussed, fiber volume, count, modulus, surface area, geometry, end anchorage, distribution, and aspect ratio all contribute to the properties of FRC.

Steel and polymeric fibers have been shown to be the most effective materials to reinforce FRC because of their tensile strengths, moduli of elasticity, and bond characteristics. To date, steel fibers have had a decided structural advantage over the polymeric fibers because they are stronger and have produced FRC with superior structural properties. A new polymeric fiber and unique delivery system developed by the 3M Company show a potential for providing FRC with properties similar to steel FRC.

Steel fibers. Steel fibers were first used to reinforce concrete in the 1960's and are now available in a number of shapes, sizes, and metal types. Cross-section shapes can be round, rectangular, or crescent. Diameters (or equivalent diameters) range from approximately 0.25 to 0.80 mm (0.01 to 0.03 in.), while lengths range from approximately 13 to 64 mm (0.51 to 2.52 in.). Currently, they are produced by three different processes: (a) metal sheets are cut into ribbons, producing a square or rectangular fiber; (b) cold drawn wire is chopped to specific lengths; and (c) melt-extracted fibers are produced by rotating a cooled disc with indentations of the size of the fiber in the surface of a molten pool of high-quality metal. Some producers of the cold drawn wire fibers collate the fibers into small bundles of 10 to 30 fibers held together with a water-soluble glue, which facilitates handling and dispersion into the concrete mixture during mixing. Cold drawn wire fibers are frequently produced with deformed or hooked ends which provide end anchorage for the fibers in the concrete matrix. This allows the fibers to be

used in smaller quantities because the fibers develop higher pullout resistance. Cut sheet fibers are also frequently deformed or corrugated. The cut sheet fibers with square or rectangular shapes have more surface area than round fibers, providing more concrete bonding area. However, the additional bonding area is not necessarily as effective in providing pullout resistance as is end anchorage associated with deformed- or hooked-end fibers (Hammons, Neeley, and Smith 1992). The melt-extracted fibers generally have irregular shapes and can have a pitted or irregular surface. The various types of steel fibers for use in FRC are generally required to meet the requirements of American Society for Testing and Materials (ASTM) Standard A 820 (ASTM 1995a).

Most of the early applications of FRC consisted of using relatively high volumes of straight steel fibers of small diameter and low aspect ratios. Due in part to the lack of any significant end anchorage with the small straight fibers, higher volumes and high aspect ratios were needed to improve the flexural properties. However, the large volume of fibers created distribution problems during mixing as groups of fibers would frequently clump together and fail to fully distribute throughout the concrete mixture. This nonuniformity was commonly referred to as "balling" and also created placement difficulties.

To prevent balling, it was necessary to add the fibers to the mixer with vibrating sieves or by manual sprinkling. Hooked ends on the fibers provided the end anchorage needed to significantly improve flexural properties with smaller quantities. The smaller quantity of fibers minimized the balling difficulties somewhat; however, it remained necessary to add the fibers to the mixer by sprinkling. By collating groups of fibers together in bundles held together with water-soluble glue, one manufacturer minimized distribution difficulties. The fibers could now be easily added to the mixer with other materials without special equipment and with minimal additional labor. The improved end anchorage made it possible for smaller volumes (40 percent less) of fibers to produce the desired properties in FRC (Ramakrishnan et al. 1980). Later developments of other deformed fibers (corrugated, crimped, etc.) produced similar results (Ramakrishnan, Wu, and Hosalli 1989a).

Currently, the quantity of steel fibers most commonly used in FRC ranges from approximately 0.25 to 1 percent by volume. However, depending upon the type of fiber and other mixture parameters, larger quantities (up to 5 percent by volume) can be successfully incorporated into an FRC mixture (Hammons, Neeley, and Smith 1992). Consideration of the desired fresh and hardened properties of the FRC as well as economics usually determine the actual quantity of steel fibers to be used.

Polymeric fibers. Polymeric fibers were first used to enhance the properties of concrete in 1965 (Goldfein 1965); however, their widespread use did not begin until the late 1970's. Various types of polymeric fibers derived from organic polymers have been used, including polypropylene, nylon, polyester, polyethylene, acrylic, aramid, and kevlar. Among these,

polypropylene and nylon fibers have had the most successful commercialization. Common forms of polypropylene fibers are smooth-monofilament, twisted, fibrillated, and tridimensional mat. Nylon fibers are usually monofilament. If incorporated in sufficient quantities, polymeric fibers can enhance the flexural properties of a concrete mixture (Balaguru and Shah 1992, Neeley and Frew 1995). However, it can be difficult to achieve adequate distribution of these polymeric fibers in a concrete mixture if the quantities are in excess of about 0.3 percent by volume, especially in low-slump concrete. The quantity most commonly used is approximately 0.1 percent by volume, which can be quite effective in reducing plastic shrinkage cracking. Quantities in the range of 0.1 to 0.3 percent by volume are sometimes used as an alternative to welded wire mesh in concrete slabs. However, these small quantities are not intended to greatly enhance the structural properties of the FRC. Other shortcomings of polymeric fibers are low modulus of elasticity, poor bond with the cement matrix, combustibility[1], and low melting point. Bond to the cement matrix is improved when several fibers are twisted together, as in the types other than monofilament mentioned previously.

In an effort to enhance the engineering properties of FRC with polymeric fibers, the 3M Company has developed a polymeric fiber for use in FRC which has aspect ratios similar to those of steel fibers. These fibers, marketed under the trade name "Polyolefin," are currently available in two sizes: (a) 0.63 mm in diameter and 50 mm long, identified as Type 50/63, and (b) 0.38 mm in diameter and 25 mm long, identified as Type 25/38 (Figure 1). The proprietary delivery system developed by 3M allows these new polymeric fibers to be added to a concrete mixture in much larger quantities than can be achieved with traditional polymeric fibers, while achieving adequate fiber distribution during mixing. Uniform dispersion of the fibers in the concrete mixture is necessary to maintain desirable rheological properties of the fresh concrete for placement, consolidation, and finishing, as well as enhanced tensile properties of the hardened concrete. Ramakrishnan (1993, 1995) determined that the 3M Polyolefin fibers with the unique delivery system could be successfully added to a concrete mixture in quantities up to 8 percent by volume. A more practical range of usage was from 1 to 2 percent. Inclusion of these fibers enhanced the properties of FRC similar to that of FRC containing steel fibers. The overall performance characteristics including flexural strength and toughness, crack-growth restraint, and impact resistance were enhanced. Laboratory tests indicated that FRC with 1 percent by volume of the 3M Polyolefin fibers performed comparably to FRC with 0.25-percent volume of a popular hooked-end steel fiber.

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[1] Recent literature (Hoff 1996) (Bilodeau et al. 1997) has suggested that combustibility may be a great advantage in rendering FRC with polymeric fibers resistant to spalling in hydrocarbon fires.

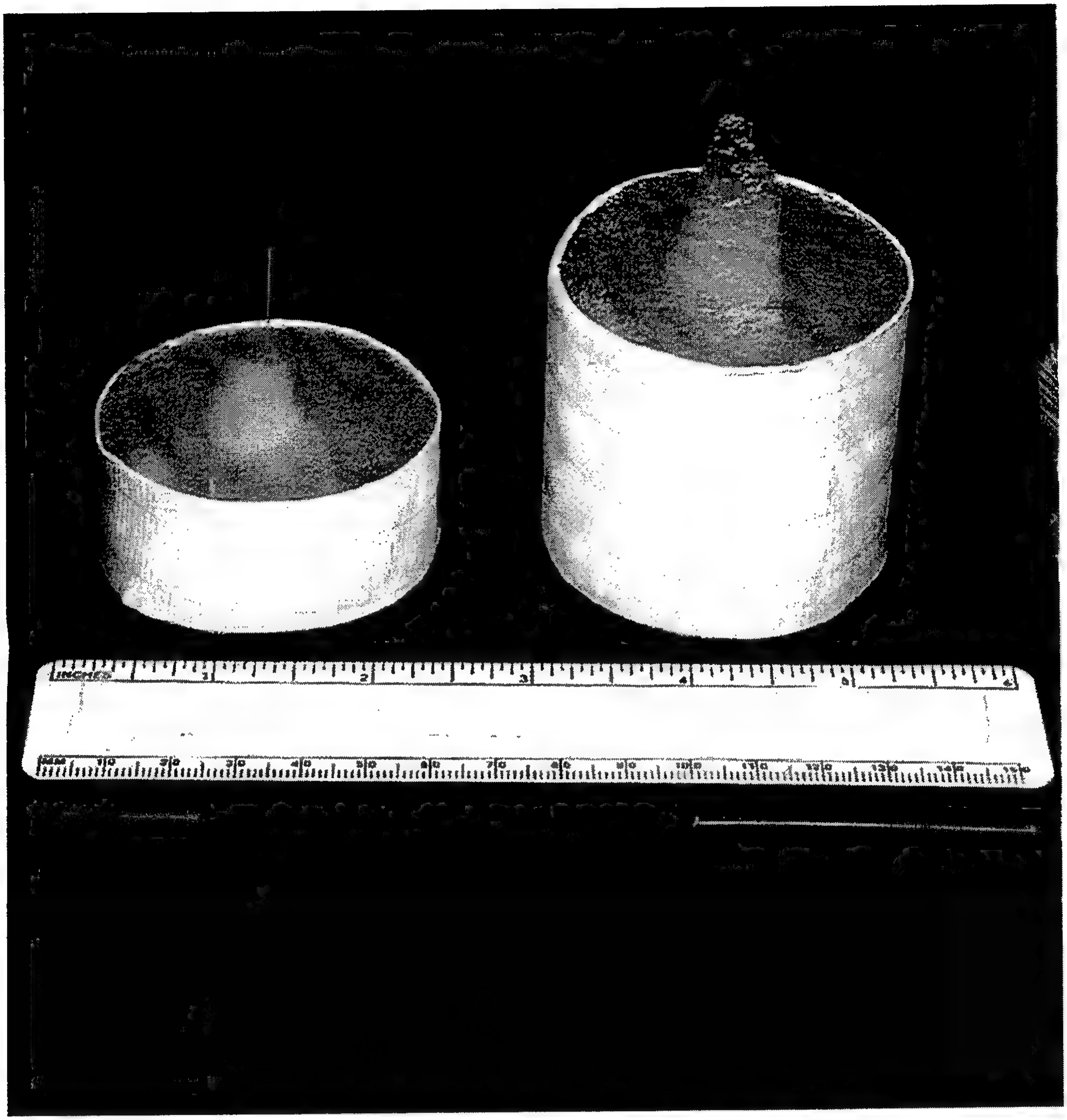

Figure 1. Polyolefin fibers, Type 25/38 (left) and Type 50/63 (right)

Overall Project Objective

The objectives of this investigation were to test, evaluate, demonstrate, and commercialize a polymeric fiber, 3M Polyolefin, which would significantly improve the overall engineering properties of FRC in a cost-effective manner,

thereby making available to the construction community a high-performance FRC with polymeric fibers suitable for applications where concrete without fibers or FRC with other types of fibers has identifiable limitations due to fresh or hardened properties, or cost.

Scope of Investigation

During this investigation, the 3M Company was responsible for commercialization of the Polyolefin fibers. 3M focused extensive attention and effort on preparing and making available literature describing the product as well as documenting case histories where the product was used. Particular attention was given to introducing the product to state departments of transportation (DOT's). Product samples were also made available to various academic institutions for evaluation purposes. Numerous papers were presented describing the academic and project work (Jagodzinski 1998; MacDonald 1998; Ramakrishnan and MacDonald 1997; Ramakrishnan, Strand, and MacDonald 1996).

The focus of the USAEWES effort during the investigation was evaluation of the performance of the fibers in FRC. A two-phase laboratory investigation was designed to evaluate various fresh and hardened properties of the FRC. A test matrix for Phase I is shown in Table 1. The primary purposes for the Phase I investigation were to (a) evaluate the effect of the fibers upon the mixture proportioning requirements to produce specified fresh properties, (b) evaluate and compare the performance of the two sizes of fibers (Type 50/63 and Type 25/38), (c) evaluate and compare different levels of fiber loading (0 to 1.64 percent, by volume), (d) briefly compare fresh and hardened properties to those of FRC produced with steel and other more traditional polymeric fibers, and (e) verify and validate previous research on Polyolefin fibers. The purpose of the Phase II investigation was to repeat selected mixtures from the Phase I investigation and evaluate additional hardened properties. A test matrix for Phase II is shown in Table 2. The third phase of the overall investigation was to participate in a significant demonstration project using FRC with the Polyolefin fibers. A description of the demonstration project, conducted jointly with the Mississippi DOT, the Federal Highway Administration, the Mississippi Concrete Industries Association and affiliated members, and 3M is given in Chapter 4 of this report.

During this investigation, some of the measurements were made and recorded in SI units, while other measurements were made and recorded in non-SI units. Non-SI units were converted to SI units using conversion values in ASTM E 380 (ASTM 1995y).

Table 1
Test Matrix

Mixture ID	w/(c+m)[1]	S/A, % Volume	Type Fiber	Fiber Loading, kg/m^3	Fiber Loading, % Volume	Specified Slump, mm	Specified Air Content, %	28-day Comp. Str	28-day Flex. Str	28-day Impact Resistance
ALO	0.40	40	None	0	0	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AL1.5	0.40	40	Polyolefin	0.9	0.10	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AL6.25	0.40	40	Polyolefin	3.7	0.41	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AL15	0.40	40	Polyolefin	8.9	0.98	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AL20	0.40	40	Polyolefin	11.9	1.32	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AM6.25	0.40	45	Polyolefin	3.7	0.41	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AM15	0.40	45	Polyolefin	8.9	0.98	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AM20	0.40	45	Polyolefin	11.9	1.32	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AM25	0.40	45	Polyolefin	14.9	0.41	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AH15	0.40	50	Polyolefin	8.9	0.98	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AH20	0.40	50	Polyolefin	11.9	1.32	38 ± 12	6.0 ± 0.5	✔	✔	✔
P2AH25	0.40	50	Polyolefin	14.8	1.64	38 ± 12	6.0 ± 0.5	✔	✔	✔
BLO	0.48	40	None	0	0	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BL1.5	0.48	40	Polyolefin	0.9	0.10	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BL6.25	0.48	40	Polyolefin	3.7	0.41	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BL15	0.48	40	Polyolefin	8.9	0.98	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BL20	0.48	40	Polyolefin	11.9	1.32	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BM6.25	0.48	45	Polyolefin	3.7	0.41	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BM15	0.48	45	Polyolefin	8.9	0.98	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BM20	0.48	45	Polyolefin	11.9	1.32	88 ± 12	6.0 ± 0.5	✔	✔	✔

[1] w/(c+m) = water cementitious material ratio; S/A = sand-total aggregate ratio.

(Continued)

Table 1 (Concluded)

Mixture ID	w/(c+m)	S/A, % Volume	Type Fiber	Fiber Loading, kg/m^3	Fiber Loading, % Volume	Specified Slump, mm	Specified Air Content, %	28-day		
								Comp Str	Flex Str	Impact Resistance
P2BM25	0.48	45	Polyolefin	14.8	1.64	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BH15	0.48	50	Polyolefin	8.9	0.98	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BH20	0.48	50	Polyolefin	11.9	1.32	88 ± 12	6.0 ± 0.5	✔	✔	✔
P2BH25	0.48	50	Polyolefin	14.8	1.64	88 ± 12	6.0 ± 0.5	✔	✔	✔
DAL33	0.40	40	Steel	19.6	0.25	38 ± 12	6.0 ± 0.5	✔	✔	✔
DAL66	0.40	40	Steel	39.2	0.50	38 ± 12	6.0 ± 0.5	✔	✔	✔
DAL85	0.40	40	Steel	50.4	0.64	38 ± 12	6.0 ± 0.5	✔	✔	✔
DAM33	0.40	45	Steel	19.6	0.25	38 ± 12	6.0 ± 0.5	✔	✔	✔
DAM66	0.40	45	Steel	39.2	0.50	38 ± 12	6.0 ± 0.5	✔	✔	✔
DAM85	0.40	45	Steel	50.4	0.64	38 ± 12	6.0 ± 0.5	✔	✔	✔
DBL33	0.48	40	Steel	19.6	0.25	88 ± 12	6.0 ± 0.5	✔	✔	✔
DBL66	0.48	40	Steel	39.2	0.50	88 ± 12	6.0 ± 0.5	✔	✔	✔
DBL85	0.48	40	Steel	50.4	0.64	88 ± 12	6.0 ± 0.5	✔	✔	✔
DBM33	0.48	45	Steel	19.6	0.25	88 ± 12	6.0 ± 0.5	✔	✔	✔
DBM66	0.48	45	Steel	39.2	0.50	88 ± 12	6.0 ± 0.5	✔	✔	✔
DBM85	0.48	45	Steel	50.4	0.64	88 ± 12	6.0 ± 0.5	✔	✔	✔
FAL1.6	0.40	40	Polypropylene	0.9	0.11	38 ± 12	6.0 ± 0.5	✔	✔	✔
FAL1.6	0.40	45	Polypropylene	0.9	0.11	38 ± 12	6.0 ± 0.5	✔	✔	✔
FAL1.6	0.48	40	Polypropylene	0.9	0.11	88 ± 12	6.0 ± 0.5	✔	✔	✔
FAL1.6	0.48	45	Polypropylene	0.9	0.11	88 ± 12	6.0 ± 0.5	✔	✔	✔

Table 2
Phase II Test Matrix

Mixture ID	7-day				14-day	28-day							60-day	90-day				
	Comp Str	Flex Str	Flex Tough-ness	Impact	Freezing & Thawing	Comp Str	Flex Str	Flex Tough-ness	Impact	Elastic Modulus	Drying Shrink-age	Chloride Permeability	Fatigue	Comp Str	Flex Str	Flex Tough-ness	Impact	Chloride Permeability
AHO	✔	✔	✔	✔	✔	✔	✔	✔	✔			✔	✔	✔	✔	✔		✔
P2AH15	✔	✔				✔	✔	✔	✔					✔	✔	✔	✔	
P2AH25	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔	✔	✔	✔	✔	✔	✔
P2AM15	✔	✔				✔	✔	✔	✔					✔	✔	✔	✔	
P2AM25	✔	✔				✔	✔	✔	✔					✔	✔	✔	✔	
BHO	✔	✔	✔	✔	✔	✔				✔	✔	✔	✔	✔	✔			✔
P2BH1.5						✔					✔							
P2BH6.25						✔					✔							
P2BH15	✔	✔				✔	✔	✔	✔		✔			✔	✔	✔	✔	✔
P2BH20						✔					✔							
P2BH25	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	
P1AH25	✔	✔				✔	✔	✔	✔	✔				✔	✔	✔	✔	
P1AM25	✔	✔				✔	✔	✔	✔					✔	✔	✔	✔	
P1BH25	✔	✔				✔	✔	✔	✔	✔				✔	✔	✔	✔	
P1BM25	✔	✔				✔	✔	✔	✔					✔	✔	✔	✔	

2 Experimental Program

General

The experimental program was designed as a three-phase investigation. Phases I and II were laboratory investigations evaluating the fresh and hardened properties of concrete with and without fibers. Phase III was a field demonstration project. The materials and concrete mixtures used in this investigation were typical of those used in pavement applications. A brief description of the materials, mixtures, and test procedures used in Phases I and II is given below. All information describing the Phase III field demonstration project is given in Chapter 4.

Materials

Except for the portland cement, the same materials were used throughout Phases I and II. Portland cement from the same source was purchased on two occasions, once for Phase I and once for Phase II. Different materials were used in Phase III. A listing of the materials is provided below. Physical properties of the materials are given in Appendix B. The numbers in parentheses following each material are Concrete and Materials Division (CMD), USAEWES, identification numbers assigned to all materials used in research programs to ensure traceability.

Cement

Portland cement, Type I (950591)

Portland cement, Type I (960294)

Lot #950591 was used for all Phase I and part of Phase II. Lot #960294 was used for part of Phase II. Chemical and physical properties of the two portland cements are given in Table B1, Appendix B. The cement met the requirements of ASTM C 150 (ASTM 1995j), Type I.

Pozzolan

Fly ash, class C (950589)

Chemical and physical properties of the fly ash are given in Table B2, Appendix B. The fly ash met the requirements of ASTM C 618 (ASTM 1995r) for Class C.

Aggregates

Natural sand fine aggregate (950640)

19.0-mm (3/4-in.) nominal maximum size (NMS) crushed limestone coarse aggregate (950635)

The sieve analysis (ASTM C 136 (ASTM 1995g)) of both aggregates and values of absorption and specific gravity (ASTM C 127 (coarse aggregate) and C 128 (fine aggregate) (ASTM 1995e and f)) are given in Table B3, Appendix B.

Air-entraining admixture

Air-entraining admixture (AEA) (950494)

The air-entraining admixture met the requirements of ASTM C 260 (ASTM 1995o).

Fibers

Polyolefin fibers, Type 25/38 (950610), 0.38 mm in diameter by 25 mm long

Polyolefin fibers, Type 50/63 (950609), 0.63 mm in diameter by 50 mm long

Steel fibers (950797), hooked ends, 0.80 mm in diameter by 60 mm long

Polypropylene fibers (950798), fibrillated, 51 mm long

Concrete Mixtures

Variables

Water-cementitious material ratio w/(c+m)

0.40 by mass

0.48 by mass

Sand-aggregate ratio (S/A) (fine aggregate - total aggregate ratio)

40 percent

45 percent

50 percent

Fiber type

Polyolefin

Steel

Polypropylene

Fiber content, percent by volume of concrete

0.10 percent (Polyolefin and polypropylene)

0.25 percent (steel)

0.41 percent (Polyolefin)

0.50 percent (steel)

0.64 percent (steel)

0.98 percent (Polyolefin)

1.32 percent (Polyolefin)

1.64 percent (Polyolefin)

Constants

Air content

6.0 ± 0.5 percent

Slump

88 ± 12 mm (4 ± 1 in.) for mixtures having a 0.48 w/(c+m)

38 ± 12 mm (2 ± 1 in.) for mixtures having a 0.40 w/(c+m)

In order to maintain a constant slump, it was necessary to increase the water content as the fiber content increased. Since the w/(c+m) was also a constant

within a given set of mixtures, the increase in water content resulted in a corresponding increase in the cementitious material. A summary of the Phase I mixture proportions is given in Table B4, Appendix B.

Identification

A series of acronyms were used to identify the concrete mixtures. A listing of the mixture designations is given below. For example, a mixture identified as "P2AM25" would have type 50/63 Polyolefin fibers, a 0.40 w/(c+m), a 45-percent S/A, and 1.64-percent volume of fibers.

Fiber type

P2. Polyolefin, Type 50/63

P1. Polyolefin, Type 25/38

D. Steel

F. Polypropylene

w/(c+m)

A. 0.40

B. 0.48

S/A

L. 40 percent

M. 45 percent

H. 50 percent

Fiber volume

1.5. 0.10 percent (Polyolefin)

1.6. 0.10 percent (polypropylene)

6.25. 0.41 percent (Polyolefin)

15. 0.98 percent (Polyolefin)

20. 1.32 percent (Polyolefin)

25. 1.64 percent (Polyolefin)

33. 0.25 percent (steel)

66. 0.50 percent (steel)

85. 0.64 percent (steel)

Test Procedures

Fresh concrete

Tests performed on the fresh concrete included slump (ASTM C 143 (ASTM 1995i)), air content (ASTM C 231 (ASTM 1995n)), unit weight (ASTM C 138 (ASTM 1995h)), vebe consistency (BS 1881: Part 104) (British Standards Institute 1983), and finishability (no standard test procedure). The finishability procedure was described by Bury, Bury, and Martin (1994) for concrete without fibers. An attempt was made to adapt the procedure to the FRC mixtures. However, difficulty was encountered in establishing test-to-test uniformity in the initial surface prior to the beginning of the floating. Due to this discrepancy, the test results were questionable and are not presented in the report.

Hardened concrete

All specimens prepared for subsequent hardened testing were fabricated according to ASTM C 192 (ASTM 1995m) and cured in a moist room ASTM C 511 (ASTM 1995q) until time of testing. Cylindrical specimens, 152 mm in diameter by 305 mm high (6 by 12 in.), were fabricated for unconfined compressive strength (ASTM C 39 (ASTM 1995b)), elastic modulus (ASTM C 469 (ASTM 1995p)), and impact (ACI 544 (ACI 1995b)) testing. The 305-mm (12-in.) long specimens were sawed into sections 63 ± 3 mm (2.5 ± 0.125 in.) thick for the impact tests. Prisms, 152 by 152 by 610 mm (6 by 6 by 24 in.), were fabricated for flexural strength (ASTM C 78 (ASTM 1995d)), flexural toughness (ASTM C 1018 (ASTM 1995t)), and fatigue testing (ACI 544) (ACI 1995b). Cylindrical specimens, 102 mm in diameter by 203 mm high (4 by 8 in.), were fabricated for chloride permeability testing (ASTM C 1202 (ASTM 1995v)). One test sample was sawed from each of the 203 mm- (8-in.-) high specimens. In an exception to the test procedure, approximately 6 mm (0.25 in.) was sawed from the top in order to remove protruding fibers and provide a relatively smooth testing surface. Next, a sample, 50 ± 3 mm (2 ± 0.125 in.), was taken from the top half of the specimen for testing. Prisms, 89 by 114 by 406 mm (3.5 by 4.5 by 16 in.) were fabricated for freezing-and-thawing testing (ASTM C 666, Procedure A (ASTM 1995s)). Prisms having a cross section of 76 by 76 mm (3 by 3 in.) and an effective gage length of 254 mm (10 in.) were fabricated for drying shrinkage testing (ASTM C 157 (ASTM 1995k)).

Compressive strength, flexural strength, flexural toughness, and impact resistance were determined in Phase I. All tests were conducted at 28-days age. In Phase II, elastic modulus, freezing-and-thawing resistance, chloride permeability, drying shrinkage, and fatigue strength were also determined.

Test ages were 7, 28, and 90 days. With two exceptions, all mixtures tested in Phase II were replicates of mixtures in Phase I.

The flexural fatigue endurance procedure (ACI 544.2R (ACI 1995b)) was used with non-reversed loading. Flexural strength of the concrete was measured (ASTM C 78 (ASTM 1995d)) to determine the average maximum load that could be supported by the beam. The range of cyclic loading in the flexural fatigue endurance procedure was then defined as a percentage of the average maximum load. The lower limit for all tests was 10 percent of the maximum load. The upper limit varied from approximately 50 to 90 percent of the maximum load. Specimens were tested at various upper loading limits until it could be determined approximately what percentage of the maximum load the concrete under test could withstand 2,000,000 cycles without failure. The frequency of loading used ranged from 12 to 20 Hz.

3 Results and Analysis

General

Data from the two-phase laboratory investigation are presented in this chapter and referenced appendices. Some discussion of unhardened concrete properties results from the whitetopping demonstration project are also presented. Unless otherwise noted, stated compressive-strength test results are the average of determinations on 3 specimens, flexural-strength and toughness results are the average of determinations on 4 specimens, impact-resistance results are the average of determinations on 15 specimens, freezing-and-thawing results are the average of determinations on 3 specimens, chloride-permeability results are the average of determinations on 6 specimens, and drying-shrinkage results are the average of determinations on 3 specimens. Approximately 20 to 25 specimens per mixture were tested during evaluation of fatigue strength. In most cases, the multiplicity of data available made it possible to perform a quite rigorous statistical analysis of the data. The conclusions drawn from this analysis are based upon considerations given to the entire body of data. The reader is cautioned against attempts to draw broad conclusions from smaller data sets within the entirety.

Fresh Concrete Properties

The concrete mixtures were batched and mixed according to ASTM C 192 (ASTM 1995m) except that the fibers were added after either 1 or 2 min of the initial 3-min mixing cycle. The specified fresh properties are given in Table 1, shown on page 7 of this report. The test results from the Phase I investigation and Phase II investigation are given in Tables B5 and B6, Appendix B, respectively. From an examination of the fresh properties data, the following observations can be made (Neeley and O'Neil 1996):

a. As shown in Figure 2, the water required to maintain a constant slump increases as the fiber loading increases.

b. With the coarse and fine aggregates used in this investigation, an S/A of 40 percent was appropriate for the mixtures without fibers. The fine-aggregate content must be increased when higher fiber loadings are used

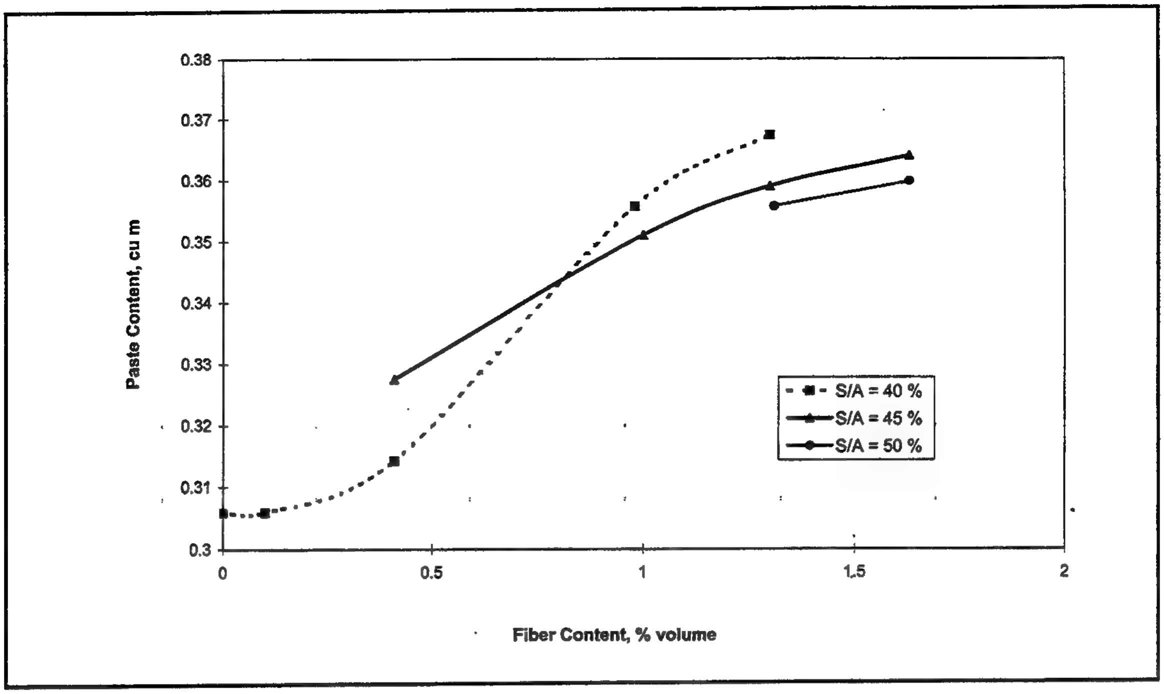

Figure 2. Paste requirement at various Polyolefin fiber contents and S/A

to prevent the concrete mixtures from being unnecessarily harsh and difficult to finish. The mixtures which are deficient in fine aggregate can visually appear to be wet, but are marginally cohesive. At an S/A of 40 percent, the Polyolefin fibers could be incorporated into the mixtures at loadings up to 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) while maintaining adequate workability. Higher fiber loadings of the Polyolefin fibers caused the mixtures to become harsh and more difficult to finish. A Polyolefin fiber loading of 11.9 kg/m^3 (20 lb/yd^3) (1.32-percent volume) required an S/A of 45 percent for adequate workability and finishability. Mixtures having a Polyolefin fiber loading of 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) were most workable and easily finished with a 50.4-percent S/A. Mixtures having a steel-fiber loading of up to 50.4 kg/m^3 (85 lb/yd^3) (0.64-percent volume) and polypropylene-fiber loadings of 1 kg/m^3 (1.6 lb/yd^3) (0.11-percent volume) had adequate workability and finishability at an S/A of 40 percent. Even at 50.4 kg/m^3 (85 lb/yd^3) (0.64-percent volume) of the steel fibers, the fiber count and fiber surface area are less than that of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) of Polyolefin fibers (Ramakrishnan 1995). Therefore, less mortar is required for workability.

c. At higher Polyolefin fiber loadings (8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) and above), an increase in the S/A sometimes decreased the water required to maintain a constant slump (Figure 2). This water reduction is the result of the mixture becoming less harsh and more cohesive. However, in determining the most efficient S/A, consideration must be given to the paste/mortar ratio (p/m) which is strongly

influenced by the w/(c+m). For w/(c+m)'s of 0.40 and above, the resulting paste content is such that some flexibility exists in choosing the proper balance between the p/m and the mortar content (strongly influenced by the S/A). When high-strength, or high-early-strength specifications require a w/(c+m) of less than 0.40, by necessity the paste content increases. When the w/(c+m) approaches 0.30, this paste increase can be significant. In these instances, as was the case with the whitetopping demonstration project described in Chapter 4, smaller increases in the S/A (3 to 5 percent) will be more effective. For example, whereas a 40-percent S/A was deemed appropriate for the mixtures without fibers in Phases I and II and a 50-percent S/A was better with 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of Polyolefin fibers, if the w/(c+m) had been close to 0.30, an S/A of 43 to 45 percent might have been more appropriate. Aggregate shape is also an influencing factor. Crushed coarse aggregates generally require a higher S/A than do more rounded natural coarse aggregates.

d. At a constant slump and S/A, an increase in the fiber-loading causes an increase in Vebe-consistency times. This occurs as the mixtures become more harsh and less workable. As shown in Figure 3, the Vebe-consistency time can be reduced by increasing the amount of fine aggregate. Again, in determining the appropriate S/A, consideration must also be given to the p/m. The Vebe-consistency test could not detect proportioning variations in the mixtures having higher slumps (88 $\pm$12-mm (4 $\pm$ 1 in.)). All Vebe times were 1 sec or less for these mixtures.

e. An increase in the dosage of AEA can be required to produce the specified air content as the fiber loading increases. Additional mixing time, especially before the fibers are added to the mixture, can be beneficial in entraining air into the mixtures. Ramakrishnan (1993) reported no difficulty in achieving proper air entrainment with normal dosages of AEA when the bundles of Polyolefin fibers were charged into a central mixer before any of the other materials, or into truck mixers after all of the other materials. Apparently the superior mixing action of a central mixer rapidly entrains air and disperses the fibers. However, when the concrete is being mixed in a truck mixer, the fibers should be added to the mixture after the concrete has been thoroughly mixed in the truck. Premature addition of the fibers to a truck mixer can interfere with proper mixing of the concrete, including entrainment of air (low air) and proper distribution of the fibers.

f. In the laboratory batches, approximately 2 to 3 min of mixing time was necessary to dissolve the water-soluble glue and disperse the tape encasing the Polyolefin fibers. The fibers appeared to distribute quickly throughout the mixture after the tape had dispersed. There was no evidence of balling, even at the higher fiber loadings. Longer mixing times were necessary when the FRC was produced in truck mixers for the whitetopping demonstration project. The concrete was mixed from 3 to 5 min prior to addition of the fibers, ensuring that the concrete was

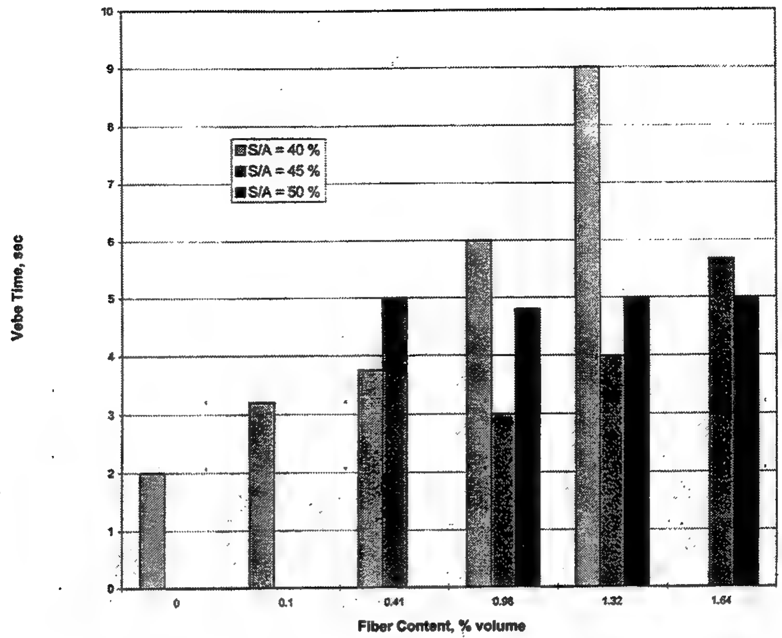

Figure 3. Effect of Polyolefin fiber content and S/A upon Vebe time

adequately mixed prior to introduction of the fibers. After the fibers had been charged into the mixer, mixing times of 8 to 10 min were required to fully distribute the fibers. The initially high slump (≥200 mm (7.9 in.)) appeared to reduce the shearing action of the mixer on the fiber bundles, therefore delaying dispersion of the tape and subsequent dispersion of the fibers. It is anticipated that depending upon factors such as batch size, mixer condition, initial slump of the mixture, and fiber loading, mixing time in a truck mixer to fully distribute the fibers will range from 5 to 10 min.

Preparation for Statistical Analysis

The first step of the analysis of the hardened properties was to search for outliers within the data sets. While proper testing procedures had been carefully followed, it should be anticipated that within sets of data this large, some outliers would be present. To improve the validity of the analysis, outliers were statistically identified using the techniques described in ASTM E 178 (ASTM 1995w) and removed from the data sets prior to final analysis.

Compressive strength

The standard deviation for properly performed unconfined compressive strength tests has been well documented and is reported in the precision and bias statement of ASTM C 39 (ASTM 1995c). The overall standard deviation

of the compressive-strength results from both phases of the laboratory investigation was comparable to that stated in test procedure C 39. The overall standard deviation of the data set being evaluated was calculated from a large data set, and its magnitude was validated by the favorable comparison to that given in procedure C 39. Therefore, the standard deviation determined from the data set in question was used in the search for outliers rather than that given in procedure C 39. A preliminary examination of the data indicated that the only variable within the investigation having a significant influence upon the compressive strength was the w/(c+m). Therefore, prior to initiating the search for outliers, the data sets were separated into two groups, one group representing each of the two w/(c+m)'s. The standard deviation for each of the two groups (1.08 for w/(c+m) = 0.48; 1.46 for w/(c+m) = 0.40 in Phase I) was determined and then used during the search for outliers within its group. Outliers within Phase I and Phase II were identified independently of each other. Averages and standard deviations before and after the outlier search are given in Tables 3 and 4 for Phases I and II, respectively. The technique described in Section 5 of ASTM E 178, "Recommended Criterion Using Independent Standard Deviation," was used to identify possible outliers. Critical values for T were taken from Table 9 of the procedure. The level of significance was 1 percent.

Phase I. Data from 63 mixtures were checked for possible outliers. Outliers were identified in 5 mixtures. One test determination was removed from the data set of each of these 5 mixtures, and a new average and standard deviation were calculated. Average compressive strength results are given in Table B7, Appendix B. Shaded cells indicate that an outlier was removed from that mixture.

Phase II. Data from 28 mixtures were checked for possible outliers. Properties were measured at 7-, 28-, and 90-days age. All mixtures were not tested at every test age. Outliers were identified in 1 mixture for 7-day data, 4 mixtures for 28-day data, and 1 mixture for 90-day data. One test determination was removed from the data set of each of these 6 mixtures, and a new average and standard deviation were calculated. Average compressive-strength results are given in Table B8, Appendix B. Shaded cells indicate that an outlier was removed from that mixture.

Flexural strength

The standard deviation for properly performed flexural-strength tests has also been well documented and is reported in the precision and bias statement of ASTM C 78 (ASTM 1995d). As with the compressive-strength results, the overall standard deviation of the flexural-strength results from both phases of the laboratory investigation was comparable to that stated in test procedure C 78. Therefore, the technique described in Section 5 of ASTM E 178 was again used to identify possible outliers. Critical values for T were taken from Table 9 of the procedure. The level of significance was 1 percent. The overall standard deviation of the data set being evaluated was used in the search for outliers rather than that given in procedure C 78. A preliminary examination of the data indicated that no variable within the investigation had a significant

Table 3
Summary of Hardened Properties Test Results, Phase I

Factor	Grouping	Compressive Strength, MPa		Flexural Strength, MPa		Impact, No. of Blows	
		Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
	all	35.61	1.06	4.86	0.25	35.93	10.76
		35.49	1.27	4.85	0.26	37.06	13.25
w/(c+m) =0.40	all A	37.68	1.46	4.92	0.31	37.42	11.79
		37.82	1.16	4.97	0.25	36.58	10.37
w/(c+m) =0.48	all B	33.48	1.08	4.73	0.26	36.67	14.84
		33.52	1.02	4.75	0.25	35.22	11.2
S/A = 50%	all H	34.67	1.05	4.85	0.26	40.64	20.51
		34.67	1.05	4.85	0.26	36.99	10.35
S/A - 45%	all M	35.90	1.12	4.79	0.26	38.73	12.50
		35.90	1.12	4.80	0.25	37.99	11.29
S/A - 40%	all L	35.52	1.47	4.92	0.32	34.73	18.68
		35.72	1.07	4.90	0.25	34.13	10.36
Steel	all D	35.87	1.55	4.92	0.37	55.79	18.68
		36.22	1.09	5.03	0.31	54.34	16.45
Polypropylene	all F	33.94	1.00	4.45	0.26	34.64	12.64
		33.94	1.00	4.45	0.26	34.64	12.64
Polyolefin Type 25/38	all P1	35.67	1.19	4.85	0.22	30.13	8.14
		35.67	1.19	4.86	0.22	29.90	7.68
Polyolefin Type 50/63	all P2	35.98	1.32	4.93	0.32	34.53	16.45
		36.06	1.03	4.97	0.26	31.65	9.42
	0	34.73	1.75	5.14	0.48	6.47	3.14
		33.89	0.68	5.32	0.23	5.82	1.97
Polyolefin	1.5	36.38	2.06	5.01	0.27	13.02	8.22
		36.84	1.37	5.01	0.27	12.08	6.18
Polypropylene	1.6	36.27	0.93	4.61	0.24	10.57	3.41
		36.27	0.93	4.61	0.24	10.57	3.41
Polyolefin	6.25	35.22	1.30	4.86	0.18	23.70	7.40
		35.22	1.07	4.86	0.18	23.37	6.90
Polypropylene	6.25	32.77	1.04	4.37	0.27	46.68	17.26
		32.77	1.04	4.37	0.27	46.68	17.26
Polyolefin	15	36.27	1.28	4.87	0.32	36.67	9.51
		36.42	1.04	4.94	0.22	33.64	7.55
Polyolefin	20	36.22	0.84	4.89	0.28	36.85	8.30
		36.22	0.84	4.89	0.28	36.53	8.93
Polyolefin	25	35.44	1.31	4.87	0.26	45.79	22.96
		35.44	1.31	4.89	0.25	41.91	12.53
Steel	33	34.38	2.95	4.44	0.24	36.18	11.68
		35.42	1.57	4.50	0.18	36.18	11.68
Steel	66	38.03	0.65	5.00	0.39	61.18	18.93
		38.03	0.65	5.08	0.32	61.18	18.93
Steel	85	35.21	1.05	5.44	0.47	70.02	25.42
		35.21	1.05	5.52	0.42	65.68	18.74

Shaded areas indicate values after outliers were removed.

Table 4
Summary of Hardened Properties Test Results, Phase II

	7-day Tests						14-day Tests		28-day Tests									
	Comp Str, MPa		Flex Str, MPa		Impact, No. of Blows		F&T Durability		Comp Str, MPa		Flex Str, MPa		Impact, No. of Blows		Modulus, GPa		Chloride Perm, C	
	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
all A	30.1	0.89	4.10	0.22	26	9	88	3	39.2	1.50	4.73	0.28	71	30	30.7	0.29	4473	946
	30.3	0.55	4.01	0.20	25	7	88	3	40.2	1.45	4.73	1.45	69	26	30.7	0.29	4473	946
all B	22.4	0.53	3.38	0.24	36	7	90	2	32.8	0.97	4.38	0.39	67	25	32.8	2.19	5641	723
	22.4	0.53	3.34	0.19	36	7	90	2	34.1	0.73	4.66	0.28	65	23	32.8	2.19	5641	723
all H	26.3	0.49	3.69	0.21	31	8	89	3	35.4	1.17	4.49	0.33	54.0	17.8	32.3	2.19	5057	834
	26.3	0.49	3.61	0.19	30	7	89	3	35.9	0.98	4.52	0.28	52.4	15.4	32.3	1.72	5057	834
all M	26.3	1.01	3.81	0.26	NA	NA	NA	NA	36.0	1.19	4.63	0.33	89.0	40.9	NA	NA	NA	NA
	26.5	0.62	3.76	0.21	NA	NA	NA	NA	36.6	1.16	4.56	0.22	88.5	37.1	NA	NA	NA	NA
all P1	26.4	0.93	3.66	0.30	NA	NA	NA	NA	34.7	1.02	4.50	0.23	70.2	23.8	29.2	0.60	NA	NA
	26.7	0.35	3.58	0.22	NA	NA	NA	NA	34.7	1.02	4.50	0.23	69.6	23.1	29.2	0.60	NA	NA
all P2	26.2	0.62	3.77	0.21	31	8	89	3	35.7	1.20	4.58	0.37	68.5	29.3	33.3	2.09	5057	834
	26.2	0.62	3.71	0.19	30	7	89	3	36.3	1.03	4.55	0.27	65.9	25.4	33.3	2.09	5057	834
0	28.8	0.73	4.08	0.29	5	1	89	3	38.5	1.40	3.87	0.29	5.2	2.5	36.5	4.90	4621	621
	28.8	0.73	3.77	0.21	5	1	89	3	38.5	1.40	3.97	0.10	4.6	1.1	36.5	4.90	4621	621
1.5	NA	NA	NA	NA	NA	NA	NA	NA	34.6	0.60	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA	34.6	0.60	NA	NA	NA	NA	NA	NA	NA	NA
6.25	NA	NA	NA	NA	NA	NA	NA	NA	34.6	0.60	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA	33.6	0.74	NA	NA	NA	NA	NA	NA	NA	NA
15	22.9	0.71	3.75	0.18	NA	NA	NA	NA	35.1	1.15	4.62	0.33	67.3	30.4	NA	NA	NA	NA
	25.9	0.71	3.75	0.18	NA	NA	NA	NA	36.9	1.15	4.62	0.33	62.1	22.6	NA	NA	NA	NA
20	NA	NA	NA	NA	NA	NA	NA	NA	32.5	0.46	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA	32.5	0.46	NA	NA	NA	NA	NA	NA	NA	NA
25	25.8	0.71	3.65	0.24	57	15	89	2	35.2	0.98	4.69	0.34	85.8	32.7	30.9	0.66	5494	1048
	26.0	0.41	3.62	0.20	56	13	89	2	35.5	0.98	4.64	0.26	85.0	31.7	30.0	0.66	5494	1048

(Continued)

Note: Shaded areas indicate values after outliers were removed.
NA - test not run

Table 4 (Concluded)

	90-day Tests							
	Comp Str, MPa		Flex Str, MPa		Impact, No. of Blows		Chloride Perm, C	
	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
all A	46.2	2.02	5.51	0.22	105	35	2749	656
	45.6	1.72	5.43	0.20	98	29	2749	656
all B	37.1	1.55	4.91	0.24	92	32	3052	754
	39.4	1.21	5.08	0.18	92	32	3052	754
all H	41.9	1.28	5.20	0.28	92	32	2900	705
	41.3	1.01	5.07	0.20	86	27	2900	705
all M	42.2	2.65	5.22	0.16	105	35	NA	NA
	41.7	1.82	5.22	0.16	104	34	NA	NA
all P1	41.5	2.87	5.58	0.12	82	20	NA	NA
	39.8	1.30	5.61	0.13	74	16	NA	NA
all P2	42.2	1.33	5.06	0.28	107	41	2900	705
	42.2	1.33	4.99	0.21	105	38	2900	705
0	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA
1.5	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA
6.25	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA
15	42.6	1.14	4.93	0.21	93	32	NA	NA
	42.6	1.14	4.88	0.14	90	26	NA	NA
20	NA	NA	NA	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA
25	40.8	2.36	5.22	0.16	101	35	3288	862
	39.8	1.46	5.19	0.16	97	33	3288	862

influence upon the flexural strength. However, it seemed prudent to again separate the data sets into two groups, one group representing each of the two w/(c+m)'s. The standard deviation for each of the two groups was determined and then used during the search for outliers within its group. Outliers within Phase I and Phase II were identified independently of each other. Averages and standard deviations before and after the outlier search are given in Tables 3 and 4 for Phases I and II, respectively.

Phase I. Data from 63 mixtures were checked for possible outliers. Outliers were identified in 6 mixtures. One test determination was removed from the data set of each of these 6 mixtures, and a new average and standard deviation were calculated. Average flexural-strength results are given in Table B7, Appendix B. Shaded cells indicate that an outlier was removed from that mixture.

Phase II. Data from 28 mixtures were checked for possible outliers. Properties were measured at 7-, 28-, and 90-days age. All mixtures were not tested at every test age. Outliers were identified in 2 mixtures for 7-day data, 2 mixtures for 28-day data, and 4 mixtures for 90-day data. One test determination was removed from the data set of each of these 8 mixtures, and a new average and standard deviation were calculated. Average flexural-strength results are given in Table B8, Appendix B. Shaded cells indicate that an outlier was removed from that mixture.

Impact resistance

The test procedure for the drop-weight impact is described in ACI 544 (ACI 1995b), but is not a standard ASTM test procedure. It is generally acknowledged that the within-batch standard deviation for this procedure can be quite large, hence the decision to make 15 determinations per mixture in this investigation. However, there is not a documented standard deviation that has been determined to be representative of a properly performed drop-weight impact test. Therefore, each set of 15 determinations for a given mixture must be considered as a single, independent sample, using the standard deviation for each sample to identify outliers within that data set. This technique, "Recommended Criteria for Single Samples," is described in Section 4 of ASTM E 178 (ASTM 1995w). Critical values for T were taken from Table 1 of the procedure. The level of significance was 5 percent. Averages and standard deviations before and after the outlier search are given in Tables 3 and 4 for Phases I and II, respectively.

Phase I. Data from 55 mixtures were checked for possible outliers. Outliers were identified in 14 mixtures. One test determination was removed from the data set of each of 11 mixtures, and two determinations were removed from the data set of 3 mixtures. A new average and standard deviation were calculated. Average impact results are given in Table B7, Appendix B. Shaded cells indicate that one or more outliers were removed from that mixture.

Phase II. Data from 28 mixtures were checked for possible outliers. Properties were measured at 7-, 28-, and 90-days age. All mixtures were not tested at every test age. Outliers were identified in 2 mixtures for 7-day data, 6 mixtures for 28-day data, and 2 mixtures for 90-day data. One test determination was removed from the data set of each of these 10 mixtures, and a new average and standard deviation were calculated. Average impact results are given in Table B8, Appendix B. Shaded cells indicate that one or more outliers were removed from that mixture.

Toughness

The test procedure for the flexural toughness is described by ASTM C 1018 (ASTM 1995t). It is generally acknowledged that the within-batch standard deviation for this procedure can be quite large, and furthermore there has also been considerable discussion (Gopalaratnam et al. 1991) about the validity of some aspects of the analysis procedure. In addition to the calculation techniques described in procedure C 1018, two previously unused modifications to the C 1018 analysis procedure were used by the authors to analyze the toughness data. These modifications affect only the way calculations were made, not the setup and running of the test. Briefly, procedure A involves inserting a point into the data set which causes the data to reflect a transition of load to the fibers at the time of major failure of the matrix without any deflection. Procedure B involves the calculation of a new parameter, called the Energy Absorption Ratio (EAR), from the original data set. The authors believe that each of these procedures present the data in such a way as to more accurately reflect the true performance of the FRC. These two alternate procedures will be described in detail, including the rational for each, later in this chapter. A third alternate analysis technique (Japan Concrete Institute (JCI) 1983) was also used to calculate another toughness parameter. This parameter is identified below as JCI. Again, this technique affects only the calculation procedure, not the way the test was set up and run. Nevertheless, the standard deviation listed in the precision statement of procedure C 1018 is applicable only to steel FRC. Its applicability to other types of FRC is cautioned against. Therefore, each set of four determinations for a given mixture was considered as a single, independent sample using the standard deviation for each sample to identify outliers within that data set. The technique again used was that described in Section 4 of ASTM E 178 (ASTM 1995w). Critical values for T were taken from Table 1 of the procedure. The level of significance was 5 percent

Phase I, original data. From toughness properties determined exactly as described in procedure C 1018, data from 59 mixtures were checked for possible outliers. Outliers were identified as follows:

a. Parameter I30. One test determination was removed from the data set of 8 mixtures.

b. Parameter I50. One test determination was removed from the data set of 8 mixtures.

c. Parameter JCI. One test determination was removed from the data set of 9 mixtures.

d. Parameter EAR. One test determination was removed from the data set of 5 mixtures.

A new average and standard deviation were calculated for the indicated data sets. Average toughness results for each parameter are given in Table B9, Appendix B. Shaded cells indicate that one outlier was removed from that mixture.

Phase I, modified data. From toughness properties determined using modification procedure A, data from 41 mixtures were checked for possible outliers. Outliers were identified as follows:

a. Parameter I30. One test determination was removed from the data set of 2 mixtures.

b. Parameter I50. One test determination was removed from the data set of 3 mixtures.

c. Parameter JCI. One test determination was removed from the data set of 4 mixtures.

d. Parameter EAR. One test determination was removed from the data set of 2 mixtures.

A new average and standard deviation were calculated for the indicated data sets. Average toughness results for each parameter are given in Table B10, Appendix B. Shaded cells indicate that one outlier was removed from that mixture.

Phase II, modified data. From toughness properties determined using modification procedure A, data from 9 mixtures were checked for possible outliers. Outliers were identified as follows:

a. Parameter I30. One test determination was removed from the data set of 1 mixtures.

b. Parameter I50. One test determination was removed from the data set of 3 mixtures.

c. Parameter JCI. One test determination was removed from the data set of 3 mixtures.

d. Parameter EAR. One test determination was removed from the data set of 1 mixtures.

A new average and standard deviation were calculated for the indicated data sets. Average toughness results for each parameter are given in Table B11,

Appendix B. Shaded cells indicate that one outlier was removed from that mixture.

Other properties

The determinations from freezing and thawing, elastic modulus, chloride permeability, and drying shrinkage were considered as single, independent samples using the standard deviation for each sample to identify outliers within that data set. The technique is described in Section 4 of ASTM E 178 (ASTM 1995w) was used to search for outliers. Critical values for T were taken from Table 1 of the procedure. The level of significance was 1 percent. No outliers were found in the freezing-and-thawing, drying shrinkage, or elastic modulus data. One outlier was removed from the chloride-permeability data. No attempt was made to remove outliers from the fatigue-strength data. Average results from freezing-and-thawing, elastic-modulus, and chloride-permeability measurements are given in Table B8, Appendix B.

Analysis of Hardened Properties

After outliers had been removed from the data, two statistical procedures (linear regression and analysis of variance) were used to analyze the various hardened properties that had been measured. Since different statistical procedures have strengths and weaknesses, it was the judgment of the authors that conclusions based upon the weight of evidence from two supporting procedures would be stronger than conclusions based upon a single analysis technique. Each analysis technique was run using SigmaStat® version 2.0 statistical software.

Mean and within-batch standard deviation values for compressive strength, flexural strength, and impact resistance for Phase I are given in Table 3, based upon the variables w/(c+m), S/A, fiber type, and fiber volume. Mean and within-batch standard deviation values for compressive strength, flexural strength, impact resistance, elastic modulus, freezing-and-thawing resistance, and chloride permeability for Phase II are given in Table 4, based upon the variables w/(c+m), S/A, fiber type, and fiber volume. The plain cells represent original data, while the shaded cells represent averages after outliers have been removed.

Compressive strength

A forward stepwise linear-regression procedure was used to search for variables within the Phase I data set which significantly influenced the dependent variable compressive strength. The independent variables were w/(c+m), S/A, fiber volume, air content, p/m, and mortar content. The probability level for accepting and deleting variables from the model was 0.05 (Type I error). A Type I error is defined as the probability that a variable will be accepted into or rejected from the model incorrectly, having as an end

result, the F statistic being the result of a chance association of random data. The procedure was run for Polyolefin Type 50/63, Polyolefin Type 25/38, and steel fibers. Since only a small number of mixtures were made using the fibrillated polypropylene fibers, and at only one level of loading, these mixtures were not included in the analysis. A summary of the results is given in Table 5. The independent variable most influencing the compressive strength was w/(c+m). This result was to be expected and further demonstrates that the addition of fibers to a properly proportioned concrete mixture does not have a significant influence upon compressive strength (Figure 4).

Flexural strength

The forward stepwise linear-regression procedure was used to search for variables within the Phase I data set which significantly influenced the dependent variable flexural strength. The independent variables were w/(c+m), S/A, fiber volume, air content, p/m, and mortar content. The probability level for accepting and deleting variables from the model was 0.05 (Type I error). The procedure was run for Polyolefin Type 50/63, Polyolefin Type 25/38, and steel fibers. Since only a small number of mixtures were made using the fibrillated polypropylene fibers, and at only one level of loading, these mixtures were not included in the analysis. A summary of the results is given in Table 5. None of the independent variables were conclusively identified as having a significant influence upon the flexural strength. This outcome was somewhat unexpected in that the w/(c+m) was not identified as a significant variable. While unexpected, this outcome is not necessarily improbable. While w/(c+m) is obviously an influencing factor in determining the flexural strength of a concrete mixture, other factors can play a larger, and perhaps more significant, role than in the case of compressive strength. While factors such as aggregate quality, shape, surface texture, and grading, etc., are all recognized as minor influencing factors in determining compressive strength, these factors can play a more significant role in determining flexural strength. The 0.08 difference in the w/(c+m) of the two mixtures may have not been large enough to produce a statistically significant difference in flexural strength given the other parameters of the mixture proportions.

One encouraging indication from the regression analysis was that increasing the S/A to facilitate workability in the mixtures having a higher fiber loading did not appear to have a negative impact upon the flexural strength. In proportioning a mixture for high flexural strength, it is generally understood that densely packed aggregate particles, especially the coarse aggregate particles, result in higher flexural strengths. Since mixtures requiring high flexural strengths are most commonly used in slab on grade or pavement applications, low slumps are usually specified. Lower slump mixtures can be proportioned to have good placement and finishing properties with less fine aggregate than can higher slump mixtures. Hence, the desire for densely packed aggregates and the ability to produce adequate workability with less fine aggregate usually result in these types of mixtures being proportioned with the absolute minimum fine-aggregate content possible. While it could be

Table 5
Results from Forward Stepwise Linear-Regression Analysis of Compressive Strength, Flexural Strength, and Impact Resistance, Phase I Data

Hardened Property	Fiber Type	Step Number	Model	R^2
Compressive strength	Polyolefin Type 50/63	1	Comp. str. = -4.789 air content + 63.084	0.305
	Polyolefin Type 25/38	1	Comp. str. = -60.246 w/(c+m) + 62.135	0.647
		2	Comp. str. = -57.516 w/(c+m) -2.074 air content + 72.733	0.728
	Steel	1	Comp. str. = -43.875 w/(c+m) + 55.190	0.360
		2	Comp. str. = -34.615 w/(c+m) - 1.788 air content +61.040	0.537
Flexural strength	Polyolefin Type 50/63	1	No model; no variables significant at 5%	
	Polyolefin Type 25/38	1	No model; no variables significant at 5%	
	Steel	1		
Impact resistance	Polyolefin Type 50/63	1	Impact = 25.091 fiber vol. + 11.279	0.791
		2	Impact = 22.383 fiber vol. + 214.812 p/m -102.881	0.854
	Polyolefin Type 25/38	1	Impact = 17.120 fiber vol. + 11.308	0.885
	Steel	1	Impact = 92.470 fiber vol. + 10.726	0.797
		2	Impact = 91.360 fiber vol. - 8.779 air content + 59.889	0.873

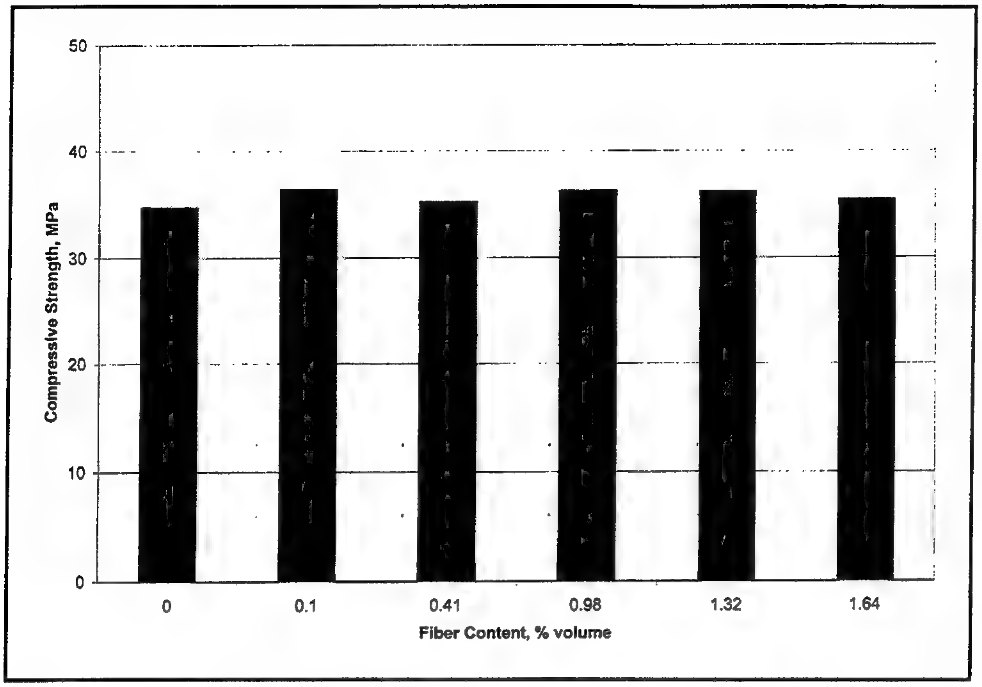

Figure 4. Effect of Polyolefin fiber content upon compressive strength

anticipated that increasing the S/A by 5, especially 10 percent, would result in a loss of flexural strength, such was not indicated by these data. It should be noted that concrete without fibers and concrete with only small amounts of fibers were not produced at the two higher S/A's in this investigation. However, in the mixtures having the larger fiber contents (8.9 kg/m^3 (15 lb/yd^3)) (0.98-percent volume) and above), increasing the S/A to 45 and 50 percent did not appear to lower the flexural strength of the concrete. The data further suggest that the addition of fibers in volumes of less than 2 percent to a properly proportioned concrete mixture does not have a significant influence upon the first-crack flexural strength (Figure 5).

Impact resistance

Regression analysis. A stepwise linear-regression procedure was used to search for variables within the Phase I data set which significantly influenced the dependent variable impact resistance. The independent variables were w/(c+m), S/A, fiber volume, air content, p/m, and mortar content. The procedure was run for Polyolefin Type 50/63, Polyolefin Type 25/38, and steel fibers. A summary of the results is given in Table 5. The independent variable most influencing the impact resistance was fiber volume. This result was to be expected (Ramakrishnan 1995) and further demonstrates that the addition of fibers to a properly proportioned concrete mixture improves the impact resistance (Figure 6). While the p/m (one occasion) and air content (one occasion) of the independent variables were also identified as influencing variables, their contribution to the ability of the equation to accurately predict the impact resistance was small. Furthermore, an examination of confounding

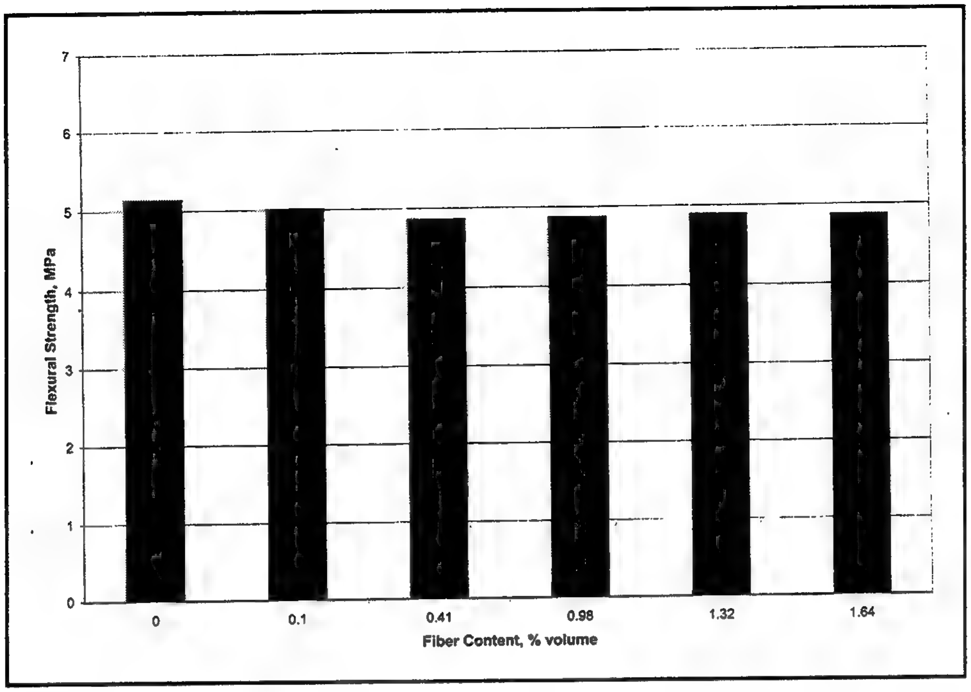

Figure 5. Effect of Polyolefin fiber content upon flexural strength

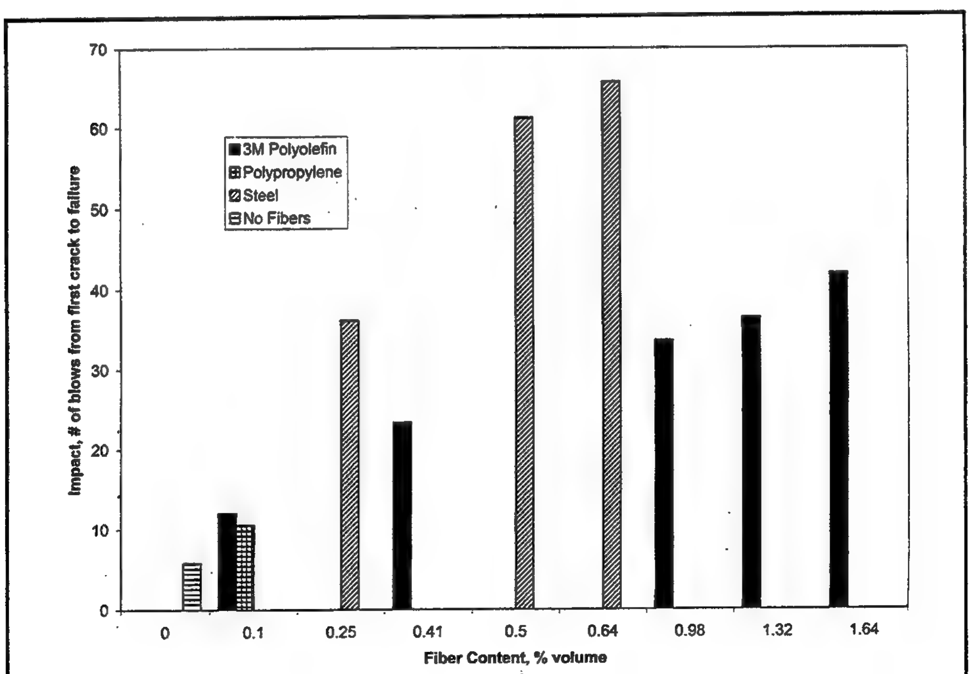

Figure 6. Effect of fiber content upon impact resistance

data (Tables C1-C3, Appendix C) suggested that their apparent contribution could also be attributed to the fiber volume. Therefore, it was concluded the only significant factor was the fiber volume. Since the significant independent variable (fiber volume) had only one level of loading for the fibrillated polypropylene fibers, the regression procedure was not a viable analysis technique for these fibers.

An examination of the regression coefficients for the impact resistance (Figure 7) indicates similar, but statistically different, performance between the two sizes of Polyolefin fibers. While the slopes of the regression lines are similar, the standard errors of the two coefficients do not overlap, suggesting statistically different performance. The regression coefficient for the steel fibers was significantly different from those of the Polyolefin fibers.

An examination of the regression lines (Figure 8), with their corresponding 95-percent confidence interval lines, suggests similar performance between the two sizes of Polyolefin fibers at lower fiber loadings. However, once the fiber volume approaches approximately 1 percent, the confidence interval lines no longer overlap, indicating a performance advantage for the larger Type 50/63 fiber.

Analysis of variance. A two-way analysis of variance procedure was used to further analyze the Phase I impact data. The purpose was to better define, if possible, the interrelationships between the fiber types and fiber volumes, especially those of the Polyolefin fibers. The dependent variable was again impact resistance. Independent variables were fiber type and fiber volume. With few exceptions, the results support the conclusions drawn from the regression analysis. A summary of the general indications is given below. A more detailed listing of the analysis can be found in Table C4, Appendix C.

a. The level of performance between the Polyolefin Type 50/63 and Polyolefin Type 25/38 was statistically different at fiber loadings of 0.41-percent volume and above.

b. With one exception, each fiber loading within both the Polyolefin Type 50/63 and Polyolefin Type 25/38 fibers resulted in statistically different impact results.

A preliminary examination of the impact data suggested that the Phase I and Phase II data were different. Therefore, the two-way analysis of variance procedure was also used to analyze the 28-day Phase II impact data separately from the Phase I data (Table C5, Appendix C). Since the Phase II data set was not as complete as that from Phase I, the analysis was less rigorous. However, the results support the conclusion from Phase I that (a) the level of performance between the Polyolefin Type 50/63 and Polyolefin Type 25/38 was statistically different and (b) different fiber loadings resulted in statistically different impact results.

In an effort to validate the earlier inference that the impact results from Phases I and II were different, the two-way analysis of variance procedure was again used. Impact data at 28-days age were compared. First using

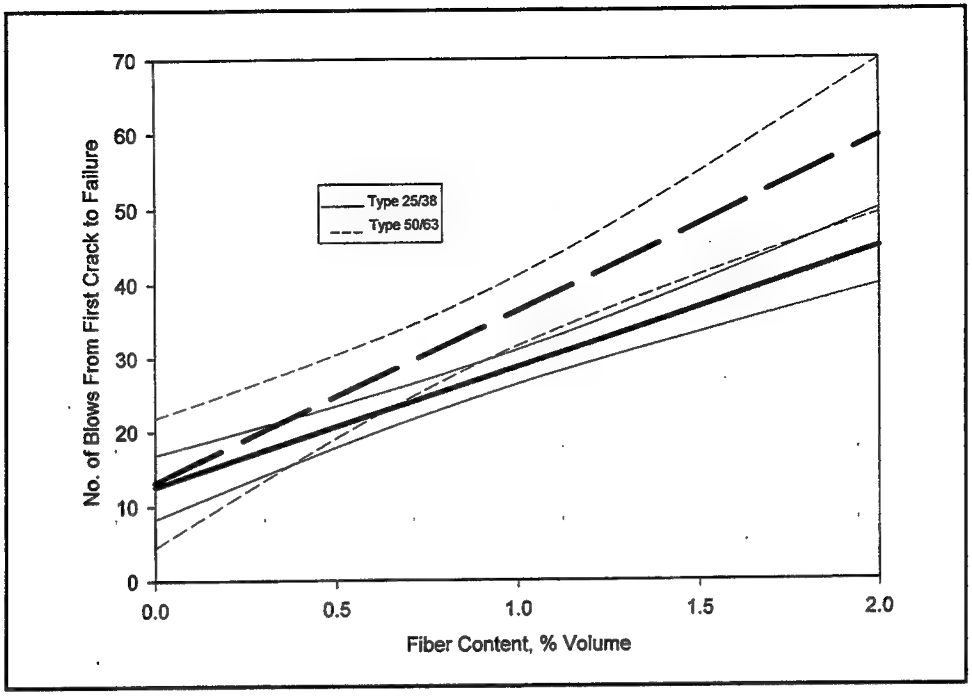

Figure 7. Impact linear regression lines with 95-percent confidence interval lines for Polyolefin fibers, Phase I data

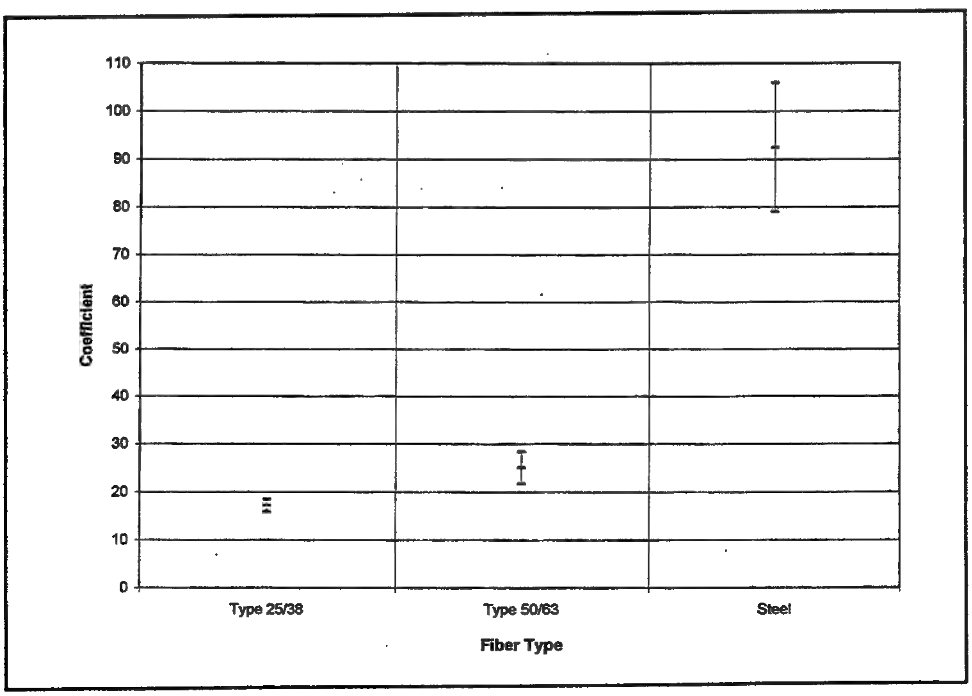

Figure 8. Impact linear regression coefficients and standard error bars

independent variables of phase number and fiber type and secondly using independent variables of phase number and fiber loading, each analysis indicated that the impact results from Phase I were statistically different from those of Phase II (Table C6, Appendix C). Indications are that the impact results from Phase II are higher than those from Phase I (Figure 9). Possible reasons for this discrepancy are discussed in Chapter 5.

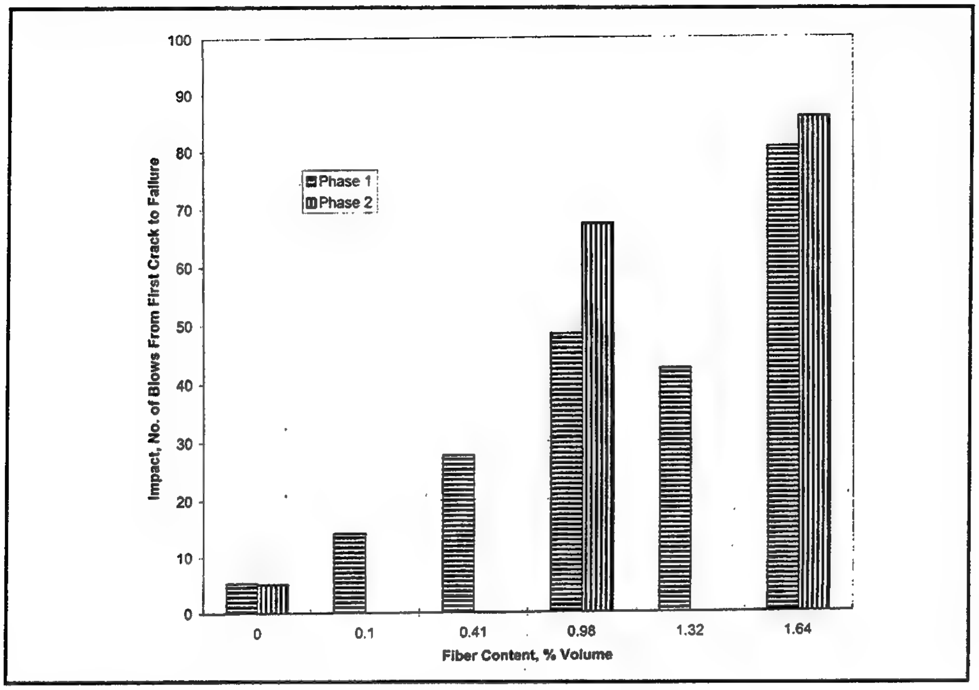

Figure 9. Comparison of impact resistance from Phases I and II

Toughness

Modifying the data set. As shown in Figure 10, addition of Polyolefin fibers in various quantities improved the post-crack flexural toughness of FRC. However, as was mentioned earlier in this chapter, due to some concerns about the validity of some aspects of ASTM C 1018 (ASTM 1995t), two previously unused procedures were used in analyzing the data. Procedure A involved inserting a point into the data set which causes the data to reflect a transition of load to the fibers at the time of major failure of the matrix without any deflection (Figure 11). Whereas an actual recorded load-deflection curve could be defined as points ABC in Figure 11, the modified load-deflection curve would be defined as points AB′C. In effect, this results in the data indicating an immediate transition of stress from the cementitious matrix to the fibers bridging the developing crack. It is recognized that this is not exactly what occurs. Obviously, there is a gradual (very fast but nevertheless gradual) transition of the stress. However, depending upon the type of fibers being used and the fiber loading, a large deflection can be reflected in the data during this transition phase. When comparing different types of fibers and fiber loadings, this deflection can have a significant influence upon the calculated index values and therefore make interpretation of the data difficult. Even

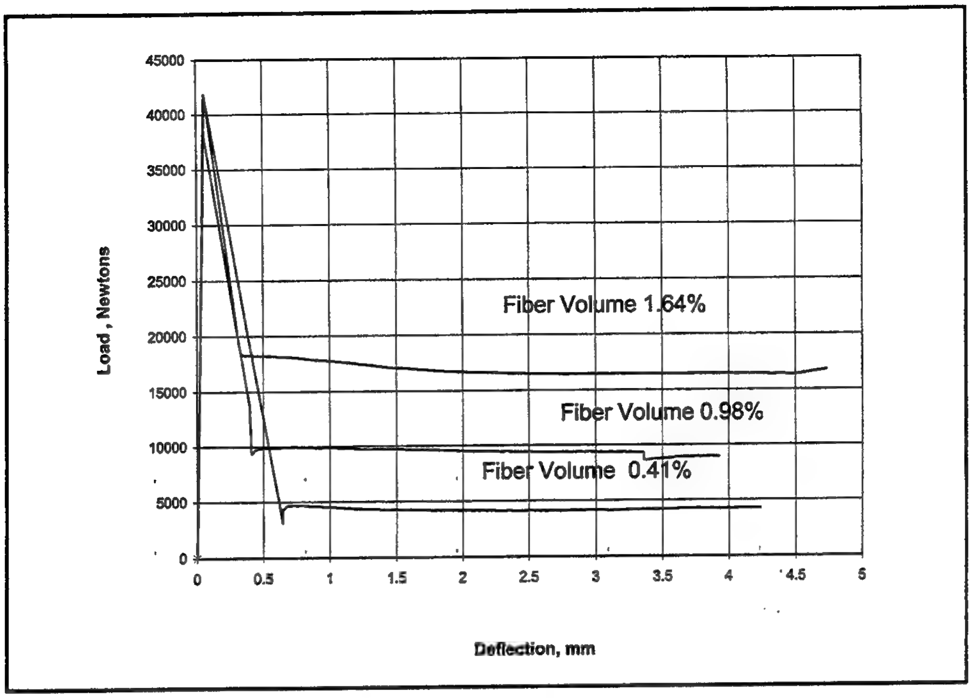

Figure 10. Load-deflection curves for various quantities of Polyolefin Type 50/63 fibers, series P2BM, Phase I

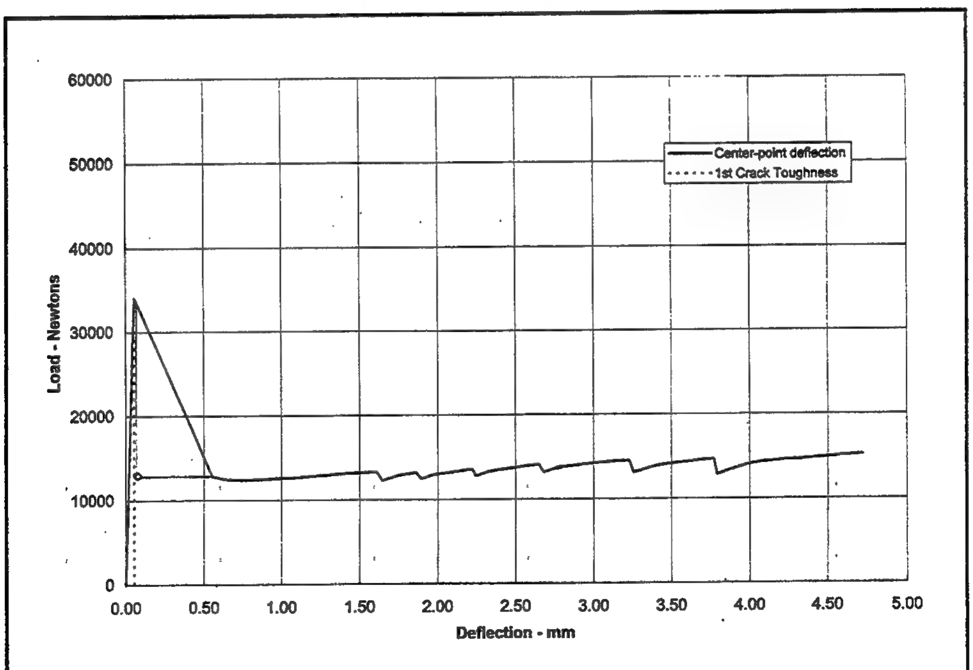

Figure 11. Typical load-deflection curve illustrating modification procedure A

worse, failure to recognize this weakness in the test procedure can lead to a misinterpretation of the data suggesting that an FRC with a low fiber content could have higher toughness values than that of a mixture with a higher fiber content. While not necessarily the perfect solution, the procedure described above does allow a reasonable comparison of the toughness indices of FRC mixtures having different types of fibers and fiber volumes.

Defining the EAR. Since strong objections can logically be made about adding a point to the original data set, Procedure B simply involves the calculation of a new parameter, EAR, from the original data set. The EAR is defined as the ratio of the energy absorption rate maintained after first crack to the energy absorption rate experienced up to first crack. This technique compares the load-deflection data prior to first crack to that after the load has been completely transitioned to the fibers bridging the crack. The portion of the load-deflection curve representing the transition is eliminated from the calculation. The value is determined as follows:

a. Integrate the load-deflection curve. As shown in Figure 12, the recorded load-deflection curve could be defined by the points OABC. Corresponding points on the integrated curve would be defined as OA′B′C′. Points A and A′ represent the point of major failure of the concrete matrix. Sections AB and A′B′ represent the transition of load from the concrete matrix to the fibers bridging the crack. Points B and B′, referred to as the transition point, represent the point where fiber yielding and slippage stabilize, and the fibers begin to consistently carry load across the crack.

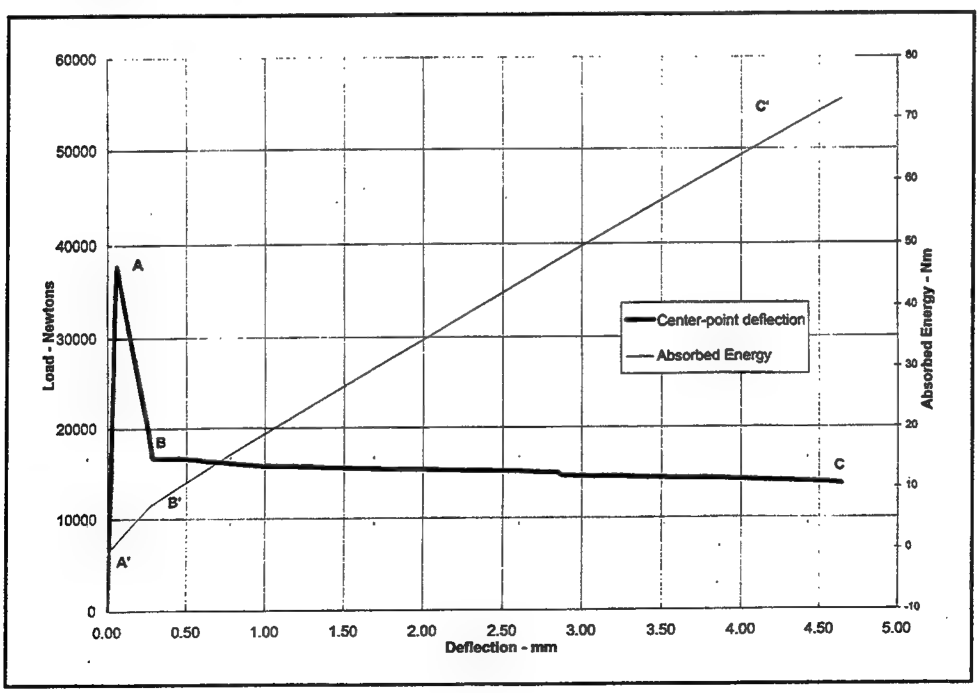

Figure 12. Typical load-deflection curve illustrating determination of the EAR

b. Calculate the slope of the line representing the area under the load-deflection curve from initial to first crack (OA′).

c. Calculate the slope of the line representing the area under the load-deflection curve from the point where the load has been transitioned to the fibers to a point representing a deflection 1/100th of the span length of the test specimen (B′C′).

d. Calculate the EAR as the ratio of the slope of the line after the transition point to the slope of the line up to first crack.

$$\mathrm{EAR} = \frac{\text{slope of } B'C'}{\text{slope of } OA'}$$

For concrete without fibers, the EAR will be zero. FRC having low fiber volumes of polymeric fibers will typically have EAR values of approximately 0.1 to 0.2. As fiber loading increases, whether polymeric or steel, the EAR values will increase. Typical EAR values for the higher loadings of the Polyolefin fibers and steel fibers in this investigation ranged from approximately 0.50 to 1.00, and in a few instances exceeded 1.00. It is believed that the EAR provides an accurate representation of the post-crack load-carrying capability of FRC, especially at larger deflections.

Regression analysis. Both the original data set and the data set modified as described above in procedure A were initially analyzed. A stepwise linear-regression procedure was used to search for variables within the Phase I data set which significantly influenced the dependent variables I30, I50, JCI, and EAR. The independent variables were w/(c+m), S/A, fiber volume, air content, p/m, and mortar content. The procedure was run for Polyolefin Type 50/63, Polyolefin Type 25/38, and steel. A summary of the results is given in Table 6. The independent variable most influencing each of the values describing toughness was fiber volume. This result was to be expected (Ramakrishnan, Wu, and Hosalli 1989b) and further demonstrates that the addition of fibers to a properly proportioned concrete mixture improves the flexural toughness (Figures 13-16).

An examination of the regression coefficients from the modified data set (Figures 17-20) for each of the dependent variables indicates similar performance between the two sizes of Polyolefin fibers. While the slopes of the regression lines are different, their similarities suggest that the differently sized fibers produce FRC with comparable flexural toughness performance. The regression coefficients for the steel fibers were significantly different from those of the Polyolefin fibers.

An examination of the regression lines from the modified data set (Figures 21-24), with their corresponding 95-percent confidence interval lines, also suggests similar performance between the two sizes of Polyolefin fibers. At lower fiber volumes, the Type 25/38 fiber appears to provide better toughness characteristics, while at higher fiber volumes, the Type 50/63 fiber appears to provide better toughness characteristics. However, the overlap in

Table 6
Results from Forward Stepwise Linear-Regression Analysis of Flexural Toughness, Phase I Data

Toughness	Fiber Type	Step Number	Model	R^2
I30 (original data)	Polyolefin Type 50/63	1	I30 = 6.626 fiber vol. + 8.644	0.276
I30 (modified data)	Polyolefin Type 50/63	1	I30 = 8.650 fiber vol. - 0.327	0.874
		2	I30 = 8.556 fiber vol. + 31.002 w/(c+m) - 13.767	0.938
		3	I30 = 7.224 fiber vol. + 29.771 w/(c+m) + 30.793 mortar content - 31.411	0.955
		4	I30 = 3.529 fiber vol. + 33.737 w/(c+m) + 87.062 mortar content + 82.123 p/m - 109.888	0.980
I30 (original data)	Polyolefin Type 25/38	1	I30 = 8.271 fiber vol. + 8.164	0.556
I30 (modified data)	Polyolefin Type 25/38	1	I30 = 7.362 fiber vol. + 2.269	0.483
I30 (original data)	Steel	1	I30 = 32.805 fiber vol. + 6.922	0.457
I30 (modified data)[1]	Steel	1	I30 = 36.911 fiber vol. + 3.935	0.569
I50 (original data)	Polyolefin Type 50/63	1	I50 = 10.617 fiber vol. + 13.086	
I50 (modified data)	Polyolefin Type 50/63	1	I50 = 14.460 fiber vol. -.941	0.878
		2	I50 = 14.334 fiber vol. + 41.393 w/(c+m) - 18.885	0.918
		3	I50 = 11.937 fiber vol. + 39.176 w/(c+m) + 55.431 mortar content - 50.648	0.939
		4	I50 = 4.677 fiber vol. + 46.969 w/(c+m) + 166.003 mortar content + 161.376 p/m - 204.857	0.973
I50 (original data)	Polyolefin Type 25/38	1	I50 = 10.775 fiber vol. + 12.614	0.476
I50 (modified data)	Polyolefin Type 25/38	1	I50 = 11.255 fiber vol. + 3.851	0.512
I50 (original data)	Steel	1	I50 = 61.259 fiber vol. + 10.002	0.569
I50 (modified data)[1]	Steel	1	I50 = 65.365 fiber vol. + 7.016	0.629
JCI (original data)	Polyolefin Type 50/63	1	JCI = 22.794 fiber vol. + 21.877	0.457
		2	JCI = 21.773 fiber vol. - 14.163 air content + 102.778	0.545
JCI (modified data)	Polyolefin Type 50/63	1	JCI = 32.775 fiber vol. - 2.354	0.907
JCI (original data)	Polyolefin Type 25/38	1	JCI = 22.913 fiber vol. + 18.823	0.622
JCI (modified data)	Polyolefin Type 25/38	1	JCI = 25.209 fiber vol. + 7.229	0.650
JCI (original data)	Steel	1	JCI = 143.119 fiber vol. + 18.136	0.604
		2	JCI = 107.913 fiber vol. + 878.340 p/m -444.118	0.717
JCI (modified data)[1]	Steel	1	JCI = 147.0869 fiber vol. + 15.251	0.627
		2	JCI = 111.135 fiber vol. + 896.904 p/m - 456.773	0.744
EAR (original data)	Polyolefin Type 50/63	1	EAR = 0.574 fiber vol. - 0.008	0.877
		2	EAR = 0.564 fiber vol. - 0.140 air content + 0.791	0.903
EAR (modified data)	Polyolefin Type 50/63	1	EAR = 0.565 fiber vol. - 0.031	0.888
EAR (original data)	Polyolefin Type 25/38	1	EAR = 0.415 fiber vol. +0.074	0.675
		2	EAR = 0.415 fiber vol. - 1.688 w/(c+m) + 0.816	0.729
EAR (modified data)	Polyolefin Type 25/38	1	EAR = 0.405 fiber vol. + 0.118	0.659
EAR (original data)	Steel	1	EAR = 2.315 fiber vol. + .379	0.566
EAR (modified data)[1]	Steel	1	EAR = 2.313 fiber vol. + .381	0.564

[1] Only the data from mixtures having 0.25-percent volume of steel fibers were modified.

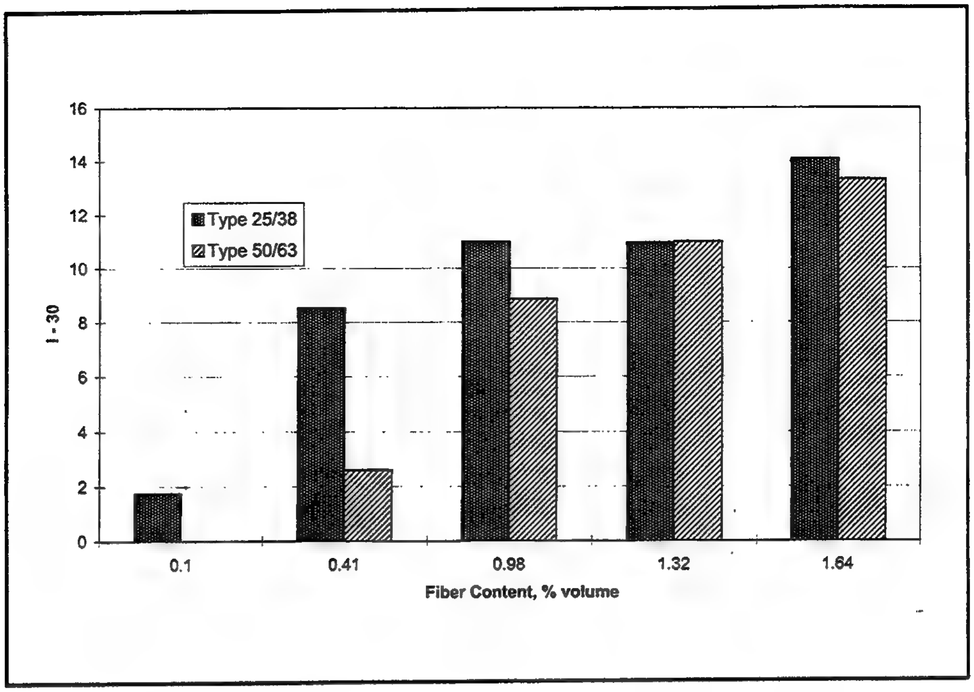

Figure 13. Toughness index I30 at various Polyolefin fiber contents, Phase I, modified data

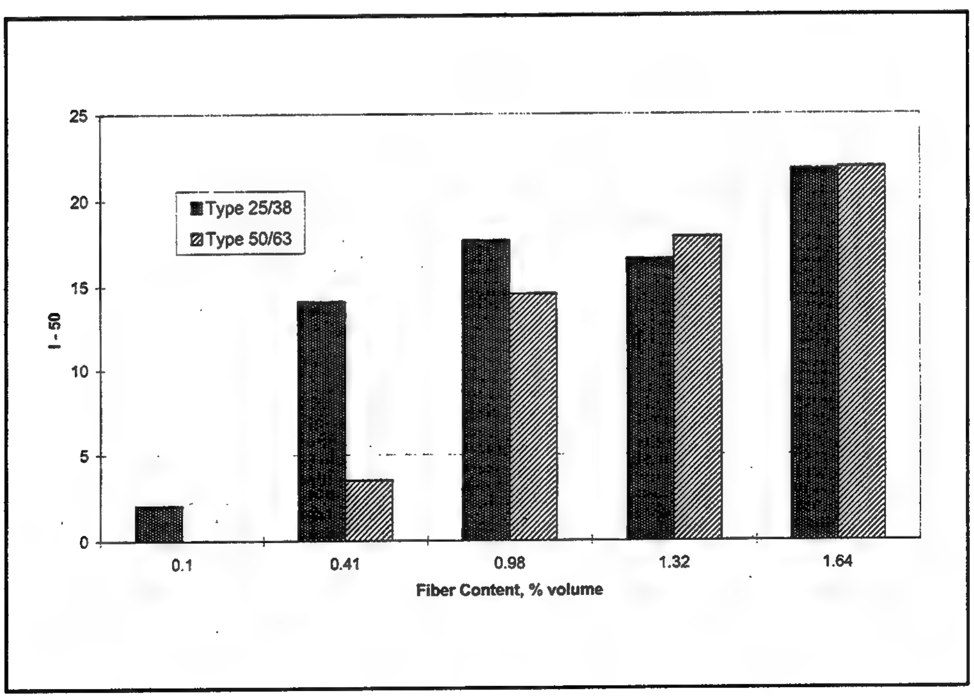

Figure 14. Toughness index I50 at various Polyolefin fiber contents, Phase I, modified data

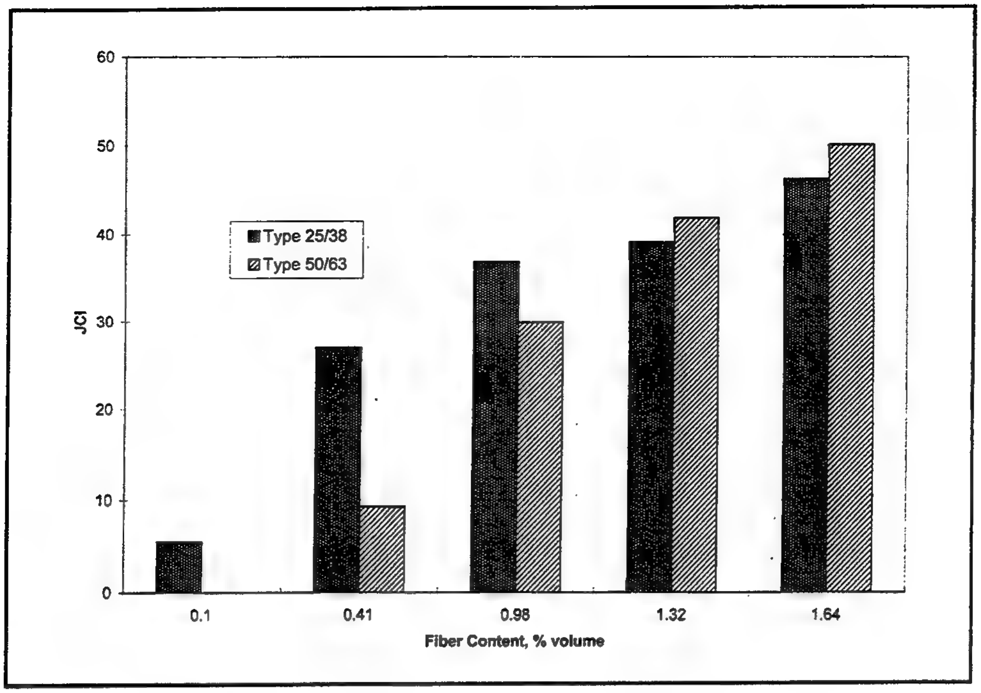

Figure 15. Toughness index JCI at various Polyolefin fiber contents, Phase I, modified data

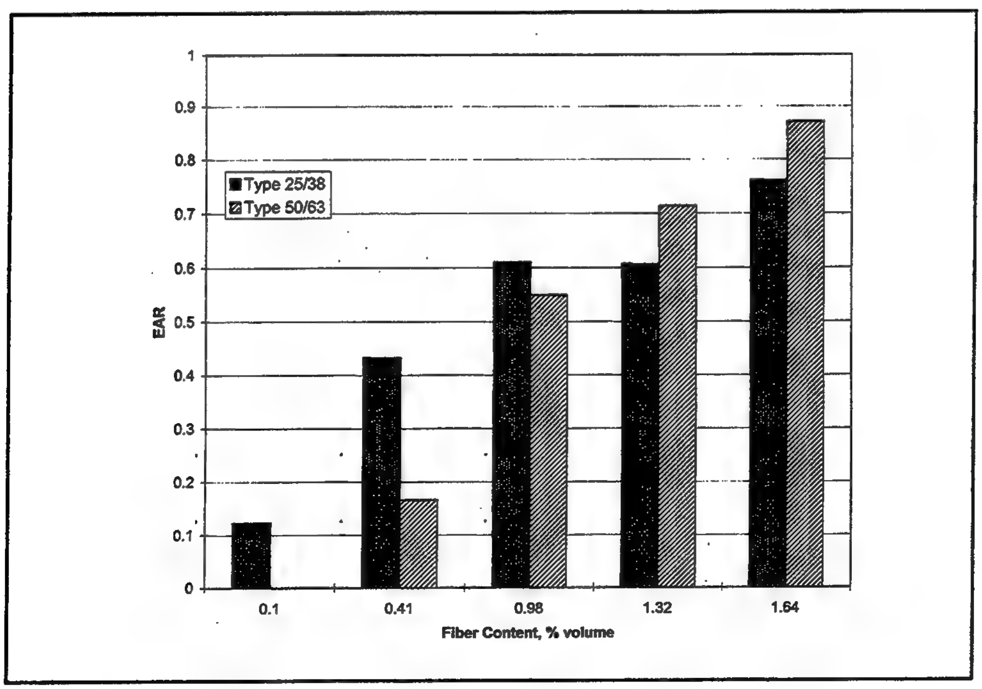

Figure 16. Toughness EAR at various Polyolefin fiber contents, Phase I, original data

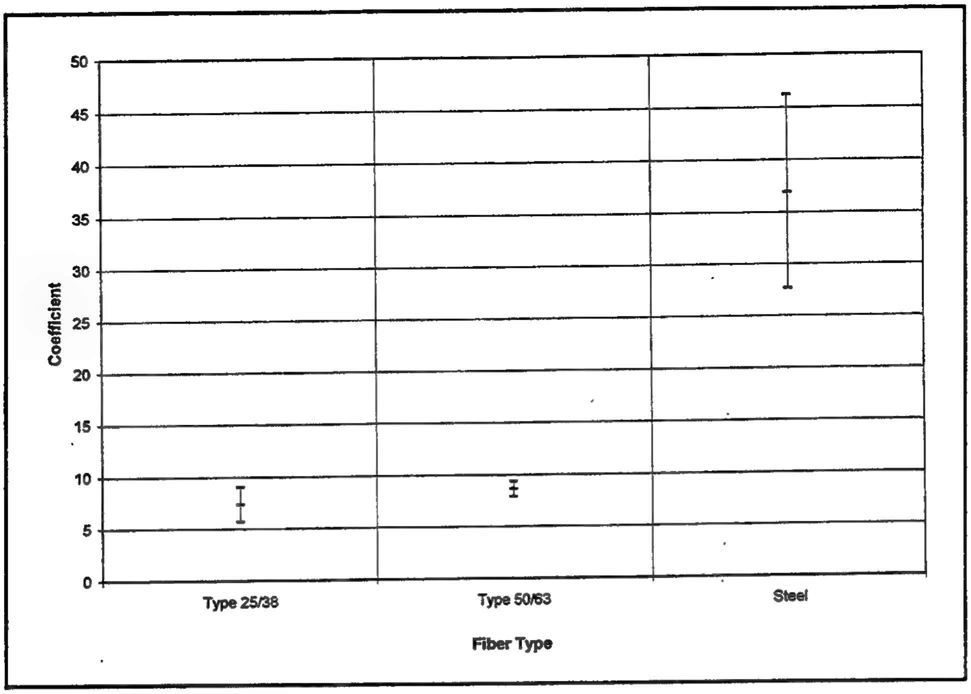

Figure 17. Toughness index I30 linear-regression coefficients, Phase I, modified data

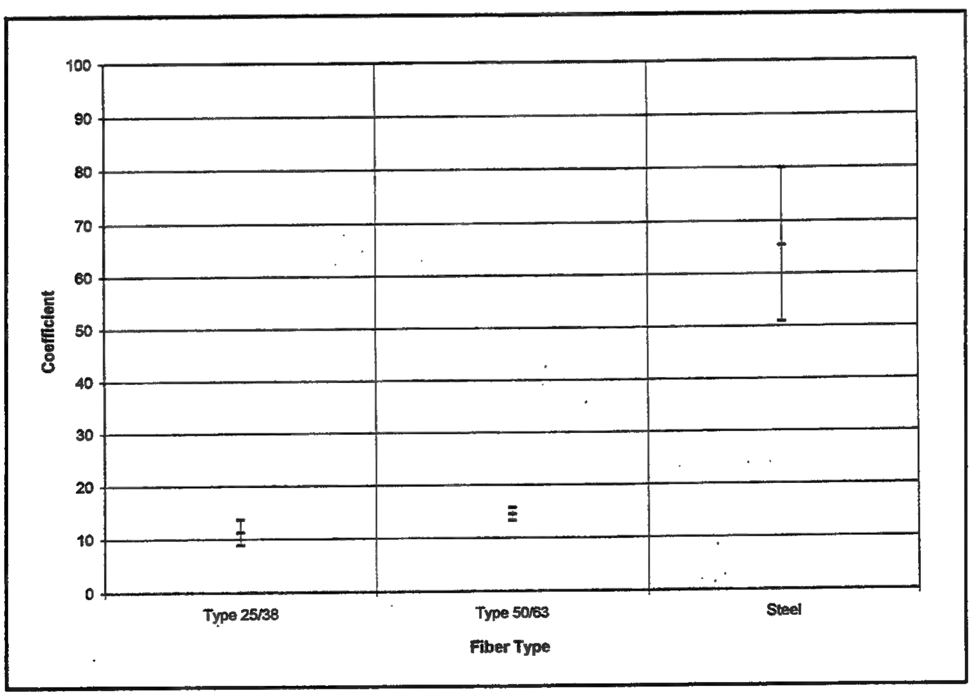

Figure 18. Toughness index I50 linear-regression coefficients, Phase I, modified data

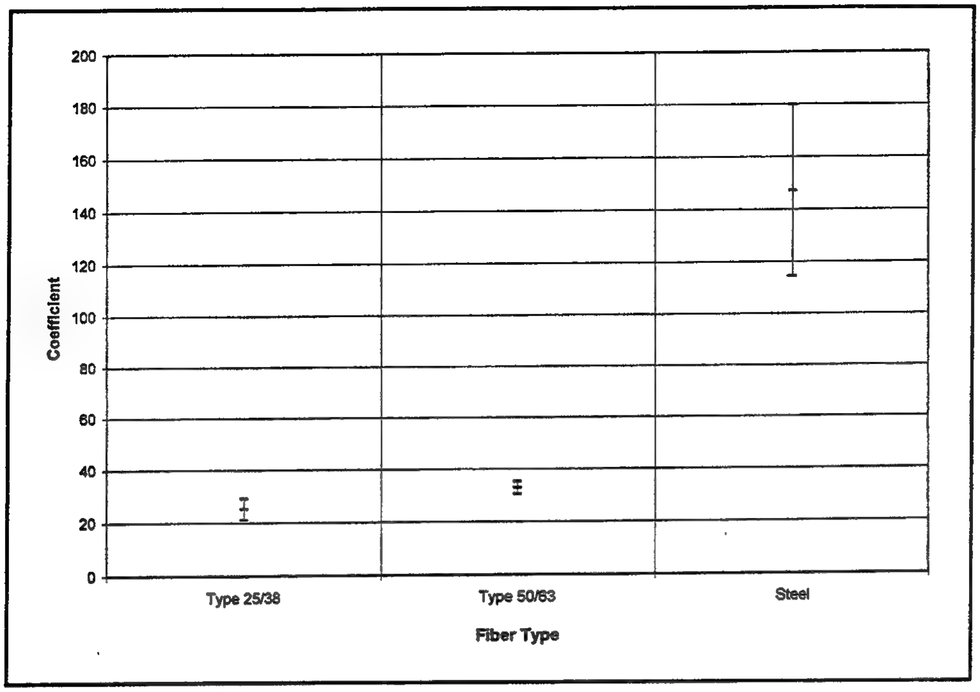

Figure 19. Toughness index JCI linear-regression coefficients, Phase I, modified data

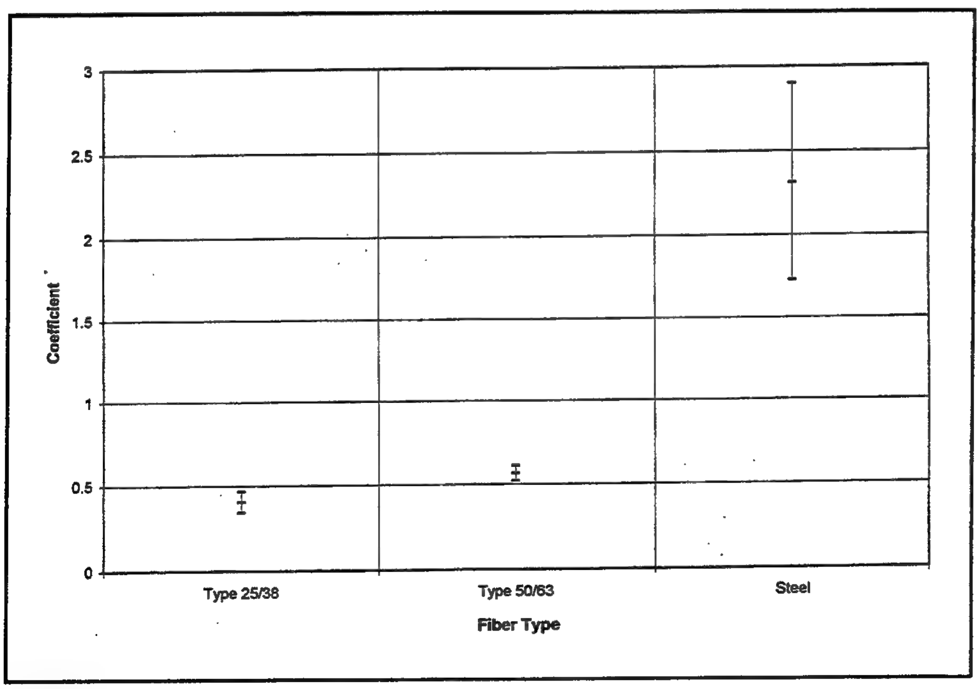

Figure 20. Toughness EAR linear-regression coefficients, Phase I, original data

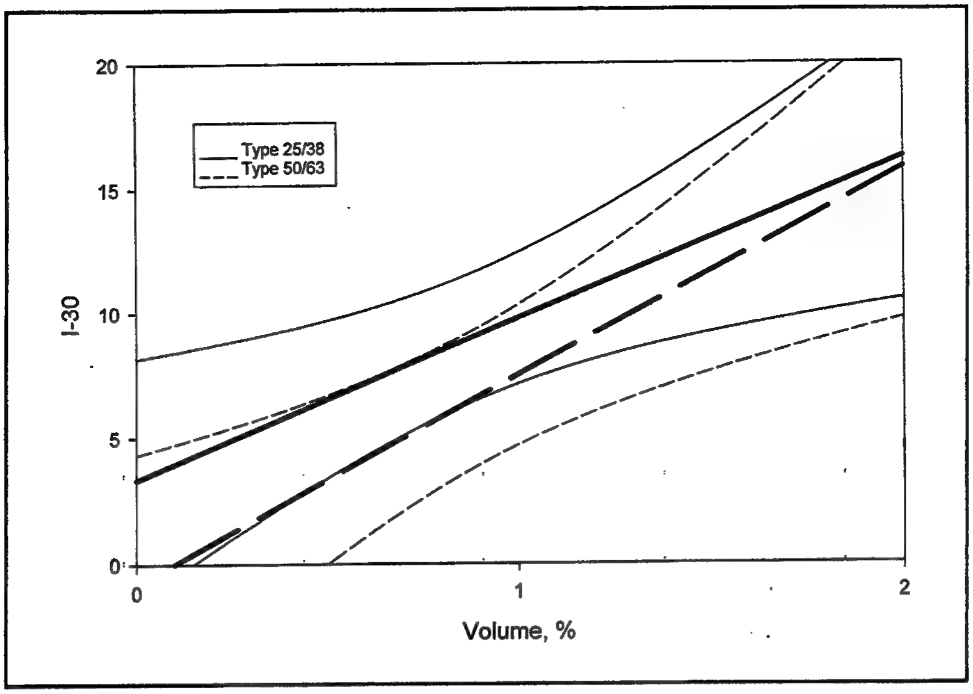

Figure 21. Toughness index I30 linear-regression lines with 95-percent confidence interval lines, Phase I, modified data

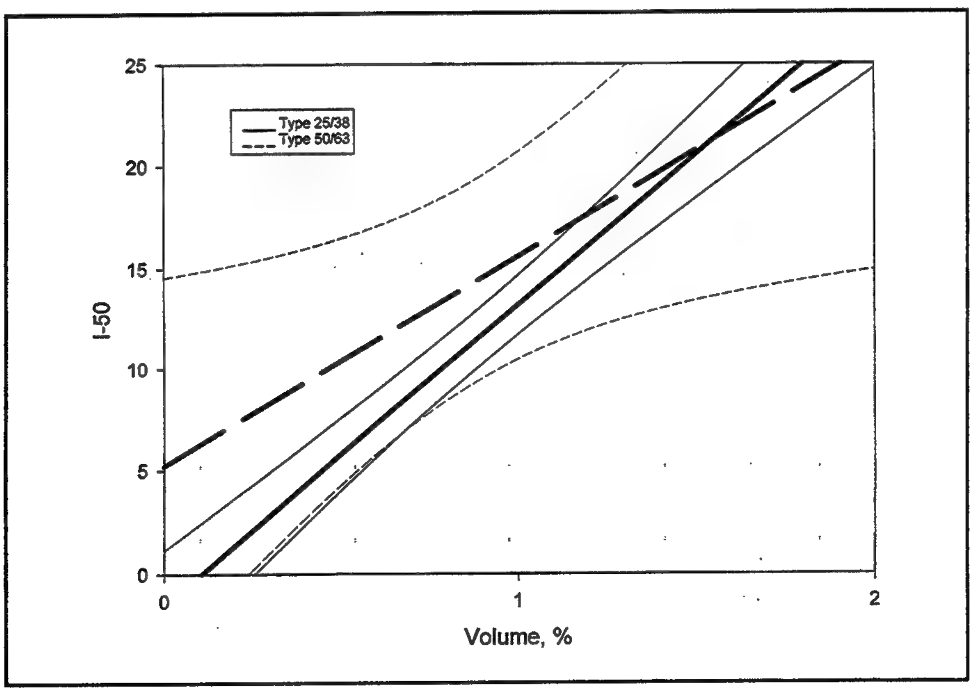

Figure 22. Toughness index I50 linear-regression lines with 95-percent confidence interval lines, Phase I, modified data

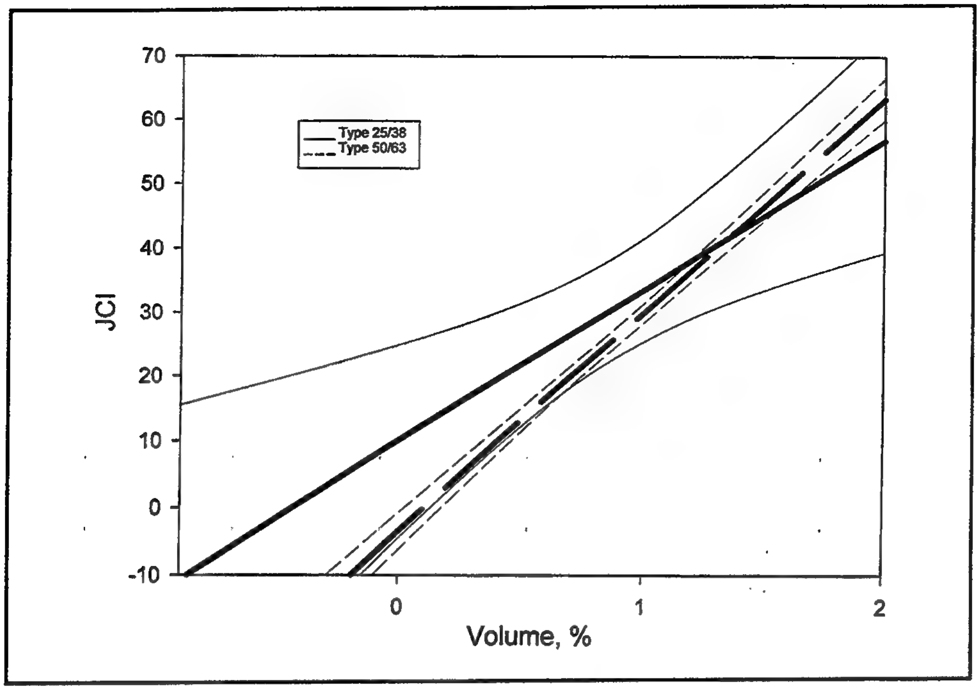

Figure 23. Toughness index JCI linear-regression lines with 95-percent confidence interval lines, Phase I, modified data

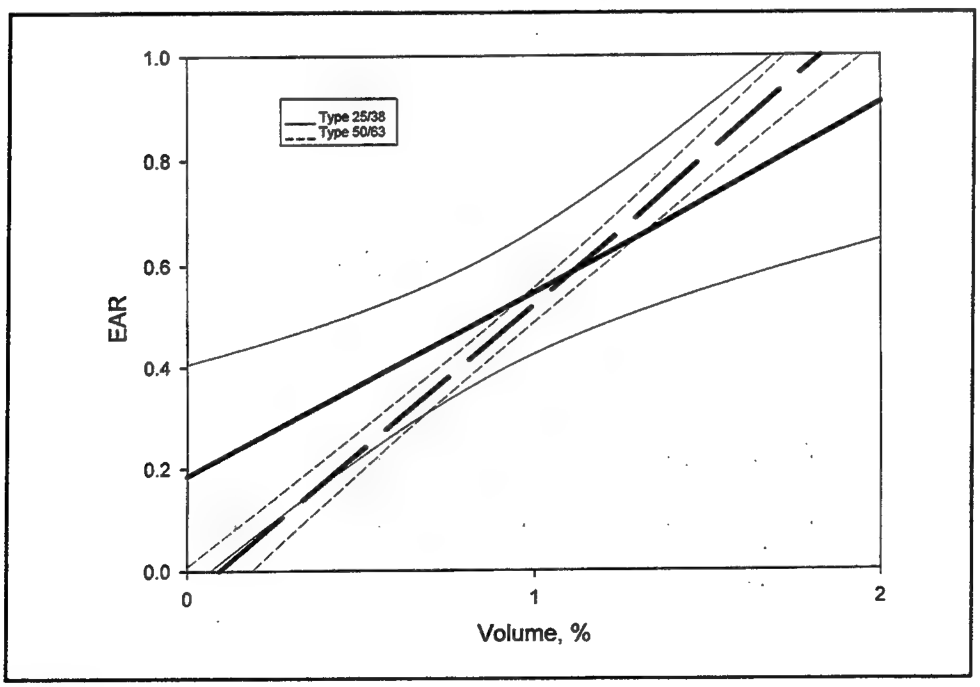

Figure 24. Toughness EAR linear-regression lines with 95-percent confidence interval lines, Phase I original data

the confidence interval lines suggests the performance is not statistically significant. This is a reasonable conclusion. It could be anticipated that when the total fiber volume is low, the FRC having the most fibers bridging a crack would have better toughness characteristics. At equal volumes, the smaller of the two fibers (Type 25/38) would have a higher fiber count. Once the fiber loading becomes such that ample fibers should be available, upon random distribution, to adequately bridge all cracks, then the longer fiber would begin to show equal and eventually superior performance at higher deflections. However, within the ranges of fiber types, fiber volumes, and loading parameters of the Polyolefin fibers used in this investigation, neither of the two Polyolefin fibers statistically demonstrated superior flexural toughness performance over the other. However, the data, especially the EAR values, suggested that at higher deflections, the larger fiber could eventually provide better performance.

A preliminary examination of the toughness data suggested that the Phase I and Phase II data were different. Therefore, the 28-day Phase II toughness data were analyzed separately from the Phase I data. A stepwise linear-regression procedure was used to search for variables within the Phase I data set which significantly influenced the dependent variables I30, I50, JCI, and EAR. Since the Phase II data set was not as complete as that from Phase I, the analysis was less rigorous. However, the results support the conclusion from Phase I that the independent variable most influencing each of the values describing toughness was fiber volume. A summary of the results is given in Table 7.

Table 7
Results from Forward Stepwise Linear-Regression Analysis of Flexural Toughness, Phase II

Toughness	Fiber Type	Step Number	Model	R^2
I30 (modified data)	Polyolefin Type 50/63	1	I30 = 13.262 fiber vol. + 0.706	0.947
I50 (modified data)	Polyolefin Type 50/63	1	I50 = 21.841 fiber vol. + 0.839	0.953
JCI (modified data)	Polyolefin Type 50/63	1	JCI = 46.855 fiber vol. + 1.858	0.966
EAR (original data)	Polyolefin Type 50/63	1	EAR = 0.965 fiber vol. + 0.023	0.922

Analysis of variance. A two-way analysis of variance procedure was used to further analyze the Phase I toughness data. The purpose was to better define, if possible, the interrelationships between the fiber types and fiber volumes, especially those of the Polyolefin fibers. The dependent variables were again I30, I50, JCI, and EAR. Independent variables were fiber type and fiber volume. While some discrepancies exist among results of the analysis of the four dependent variables, a summary of the general indications is given below. A more detailed listing of the analysis can be found in Tables C7-C10, Appendix C.

a. The effect of different fiber types (sizes) of the Polyolefin fibers depends on the fiber volume. At fiber volumes of 1.32 and 1.64 percent, there was not a statistically significant difference in performance between the two fibers. Performance was statistically different when smaller fiber volumes were used.

b. A fiber volume 0.10 percent of either of the Polyolefin fibers was not statistically different from zero fibers.

c. For each of the two fiber types, there was not a statistically significant difference between the two fiber types at fiber volumes of 0.98 and 1.32 percent, nor fiber volumes of 1.32 and 1.64 percent.

These observations generally support those of the linear regression. Items b and c above do appear to provide additional information to that of the linear regression. For purposes of making even minor enhancements to flexural toughness characteristics, 0.10 percent of either of the Polyolefin fibers is insufficient. Also, while the linear regression illustrates that toughness characteristics improve as the fiber loading increases, the magnitude of the improvement between fiber loadings of 0.98- to 1.64-percent volume were not always statistically significant.

The two-way analysis of variance procedure was then used to analyze the Phase II toughness data (Tables C11-C14, Appendix C). Since the Phase II data set was not as complete as that from Phase I, the analysis was less rigorous. However, the results generally support the conclusion from Phase I except that the Phase II data suggest that there was a statistical difference between the two fiber types at fiber volumes of 0.98 and 1.64 percent.

The two-way analysis of variance procedure was again used to further investigate the apparent difference in the 28-day Phase I and Phase II toughness data (Tables C15-C18, Appendix C). For the Polyolefin Type 50/63 fibers, the independent variables were phase number and fiber loading. The analysis of each of the four measures of toughness indicated that the toughness results from Phase I were statistically different from those of Phase II. Indications are that the toughness results from Phase II are higher than those from Phase I (Figures 25-29). Possible reasons for this discrepancy are discussed in Chapter 5.

Flexural fatigue endurance

As stated in Chapter 2, the endurance limit was defined as the maximum load at which a specimen could withstand 2,000,000 cycles of non-reversed fatigue loading. The 2,000,000-cycle limit was chosen to approximate the life span of a structure that may be subjected to fatigue loading, such as a highway pavement or a bridge deck. Brandshaug (1978) determined that specimens which could withstand at least 2,000,000 cycles would usually survive many more cycles without failure. Approximately 100 specimens having zero and 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers were tested for fatigue strength.

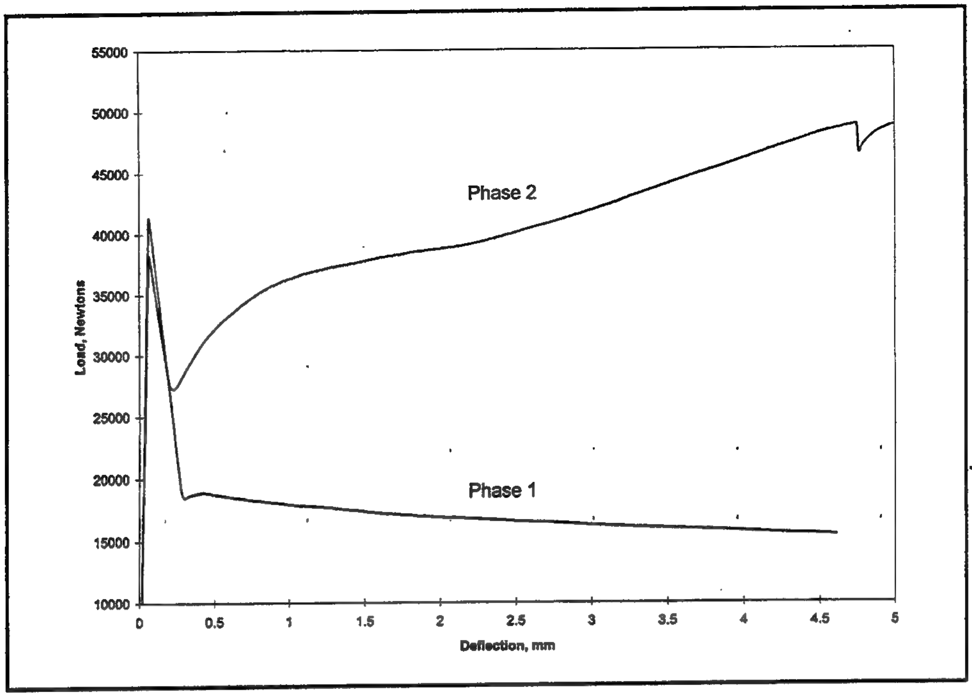

Figure 25. Comparison of load-deflection curves from Phases I and II, series P2BM25

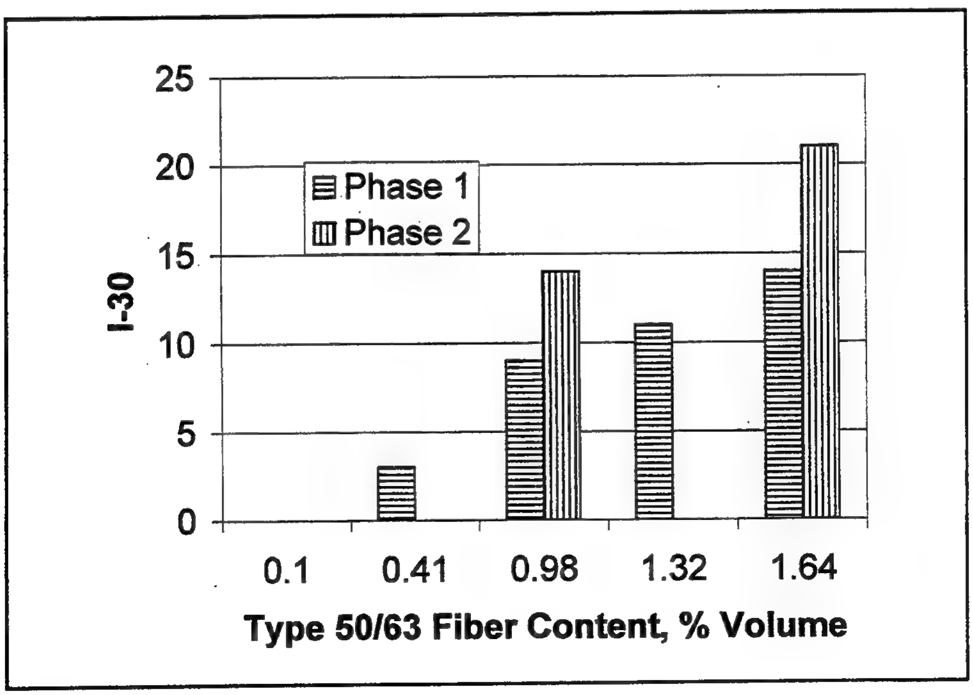

Figure 26. Comparison of toughness index I30 from Phases I and II

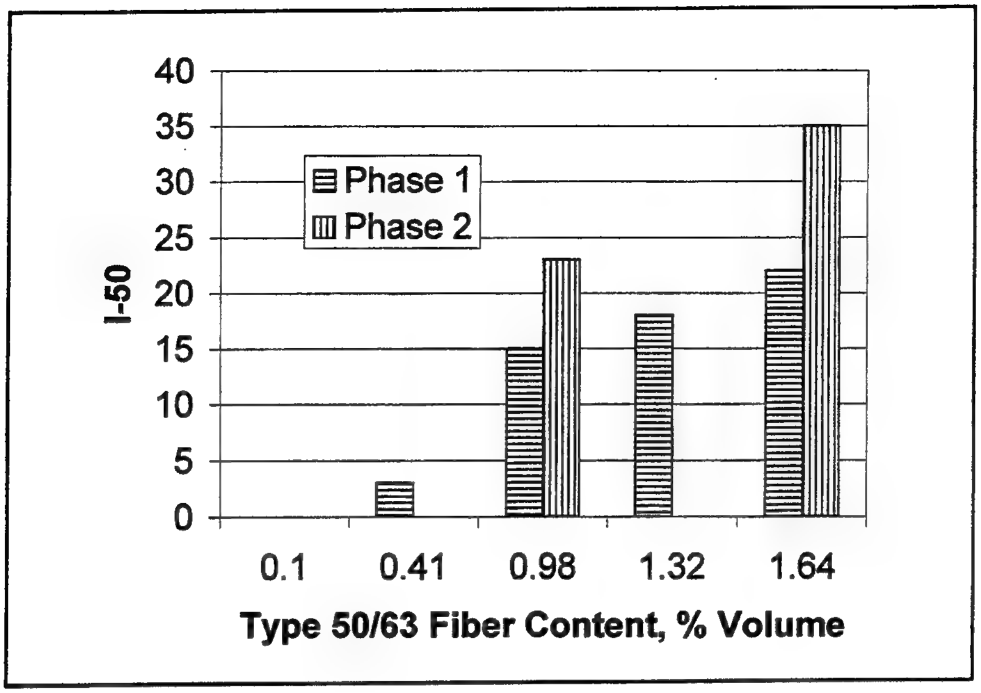

Figure 27. Comparison of toughness index I50 from Phases I and II

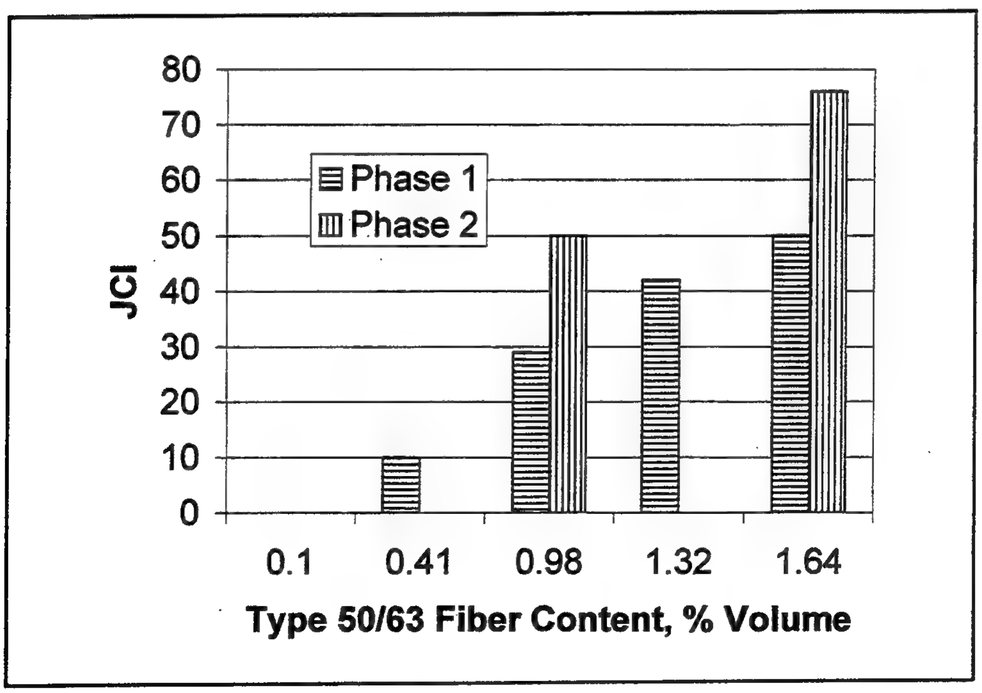

Figure 28. Comparison of toughness index JCI from Phases I and II

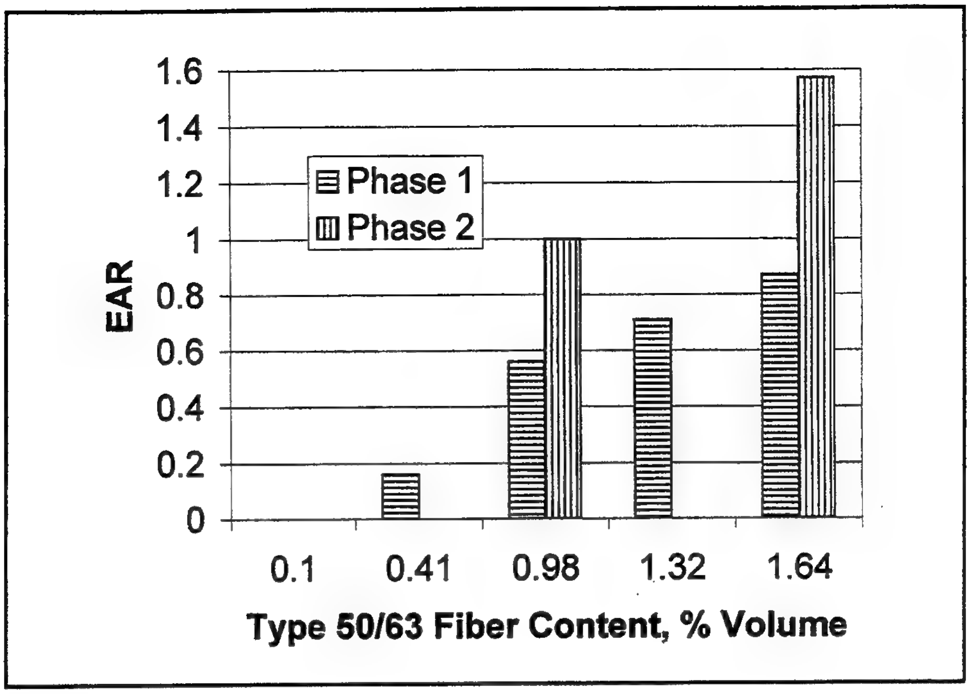

Figure 29. Comparison of toughness EAR from Phases I and II

The fatigue test results appeared to be erratic and did not correlate with results previously reported by Ramakrishnan (1995). Review of the test procedures revealed procedural errors in the test procedure throughout the testing of all fatigue specimens. The first error was failure to measure the width and depth of each specimen prior to testing. The second error was failure to adjust the minimum and maximum loading cycles according to the cross-sectional area of the specimen under test. As tested, specimen depth dimensions typically varied by approximately 2 mm (0.08 in.), while width dimensions typically varied by approximately 7 mm (0.28 in.). Failure to account for cross-sectional variations of these magnitudes can result in worse-case scenario errors in the fatigue results of up to 10 percent. While it is not believed that this amount of error was present in every specimen tested in this program, the element of uncertainty in the accuracy of the test procedure together with the erratic fatigue results provides sufficient reason to doubt the validity of the fatigue results from this investigation. Furthermore, given that differences in fatigue results between the FRC and concrete without fibers could have been approximately 10 to 20 percent, the possible error could have significantly overshadowed or magnified real differences in the fatigue endurance. Therefore the data are not included in this report.

Freezing-and-thawing resistance

Six concretes without fibers and six FRC mixtures with 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers were tested for freezing-and-thawing resistance according to ASTM C 666, Procedure A (ASTM 1995s). The relative durability factor for the 12 mixtures ranged from

81 to 98. The average relative durability factor for the 6 mixtures without fibers was 89. The average relative durability factor for the 6 FRC mixtures was also 89. This indicates that the addition of the Polyolefin fiber, even in quantities up to 14.9 kg/m^3 (25 lb/yd^3) (1.64 percent), has no measurable effect upon the freezing-and-thawing resistance of these concrete mixtures. Test results are given in Table 4.

Elastic modulus

Specimens made from one concrete mixture without fibers and three FRC mixtures with 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers were tested for elastic modulus according to ASTM C 469 (ASTM 1995p). The elastic modulus for the four mixtures ranged from 29.2 to 36.5 Gpa (4.25×10^6 to 5.30×10^6 psi). The average elastic modulus for the three FRC mixtures was 30.9 Gpa (4.50×10^6 psi). The elastic modulus for the mixture without fibers was 36.5 Gpa (5.30×10^6 psi). While the data indicate a lower elastic modulus (approximately 5 Gpa (0.75×10^6 psi)) for the FRC mixtures, this difference may not be significant. In interpreting the data, it should be considered that only one mixture without fibers was tested. The effect of the compressive strength and unit weight of the concrete should also be considered. Given these considerations, indications are that the addition of the Polyolefin fiber, even in quantities up to 14.9 kg/m^3 (25 lb/yd^3) (1.64 percent), has minimal, if any, effect upon the elastic modulus of concrete. Test results are given in Table 4.

Chloride permeability

Specimens made from two concrete mixtures without fibers and two FRC mixtures with 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers were tested for chloride permeability according to ASTM C 1202 (ASTM 1995v), except that approximately 6 mm (0.25 in.) was sawed from the top surface of the test specimen in order to provide a relatively smooth surface free of any protruding fibers. The concrete specimens without fibers were also sawed for consistency. This sawed surface was tested. At 28-days age, the charge passed for the four mixtures ranged from 3,640 to 5,682 C, indicating moderate to high chloride-ion penetrability. The average charge passed for the two mixtures without fibers was 4,621 C. The average charge passed for the two FRC mixtures was 5,494 C. Both indicate high chloride ion penetrability. At 90-days age, the charge passed for the four mixtures ranged from 2,158 to 3,339 C, indicating moderate chloride-ion penetrability. The average charge passed for the two mixtures without fibers was 2,513 C. The average charge passed for the two FRC mixtures was 3,288 C. Both indicate moderate chloride-ion penetrability. As would be expected, the chloride-ion penetrability decreased as the concrete matured. Test results are given in Table 4.

A two-way analysis of variance procedure was used to examine the possible effects of the w/(c+m) and the fiber volume upon the chloride-permeability results. The level of significance was 0.05 (Type I error). The results of the

analysis procedure can be summarized as follows: (a) w/(c+m) was significant at 28 days in concrete without fibers, but was not significant at 28 days in concrete having 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume); (b) w/(c+m) was not significant in either mixture at 90-days age; (c) fiber volume was significant at 28-days age in concrete having a w/(c+m) of 0.40, but was not significant at 28-days age in concrete having a w/(c+m) of 0.48; and (d) fiber volume was significant at 90-days age. Results of the statistical analysis are shown in Tables C17 and C18, Appendix C.

It is known that the density of a concrete mixture is a function of the w/(c+m). As the w/(c+m) decreases, density of the mortar fraction increases. Density also increases with maturity when water is available to sustain hydration of the cementitious material. Increases in density, whether from lower w/(c+m) or from increased maturity, should increase the resistance of the concrete to chloride-ion penetration. In general, the data and statistical analysis described above support this assumption. The data indicate that the chloride permeability was less for mixtures having the lower w/(c+m) and greater maturity, although the difference was not always statistically significant. Indications are that the w/(c+m) may be more significant at earlier ages when the concrete is less mature. As the concrete matures and becomes more dense, w/(c+m) may become a lesser factor. Apparently this was the case with these data where there was only a 0.08 difference in the w/(c+m).

The statistical analysis indicates a small decrease in the resistance to passage of chloride ions when 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers was present in the concrete. The difference appears to be more significant in mixtures having a denser matrix, i.e., lower w/(c+m) and more mature. A possible explanation for this phenomenon could be that the contribution of the fibers to the overall resistance to passage of chloride ions, while statistically significant at 0.05 (Type I error), is rather small. Therefore, in less dense mixtures having less resistance to the passage of chloride ions, the contribution of the fibers is somewhat overshadowed by the overall properties of the matrix. Conversely, in more dense mixtures having more resistance to the passage of chloride ions, the presence of the fibers provides discontinuities in the otherwise dense matrix sufficient to increase the passage of chloride ions.

However, caution must be exercised when interpreting the chloride-resistance results. The ASTM C 1202 (ASTM 1995v) test procedure typically produces data having a high test-to-test standard deviation. The standard deviation of the data described above was high. Procedure C 1202 cautions users against quantitative use of the numerical values of the data, suggesting a qualitative description instead. The statistical information provided above does suggest that inclusion of the fibers somewhat lessens the resistance of the concrete to passage of chloride ions. However, considering the high standard deviation of all data sets, indications are that the addition of the Polyolefin fiber, even in quantities up to 14.9 kg/m^3 (25 lb/yd^3) (1.64 percent), has only minimal effect upon the chloride permeability of concrete. From a qualitative standpoint, the effect does not appear to be significant.

Drying shrinkage

One mixture series (P2BH) was evaluated for drying shrinkage (ASTM C 157 (ASTM 1995k)) with fiber loadings ranging from 0 to 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume). The results are shown graphically in Figure 30. The results indicate that inclusion of the Type 50/63 Polyolefin fibers had no significant influence upon the drying shrinkage as determined by Procedure C 157. For further analysis of the data, all measurements were normalized to zero at initiation (Figure 31). Again, the results indicate that the Polyolefin fibers had no significant influence upon the drying shrinkage of the concrete.

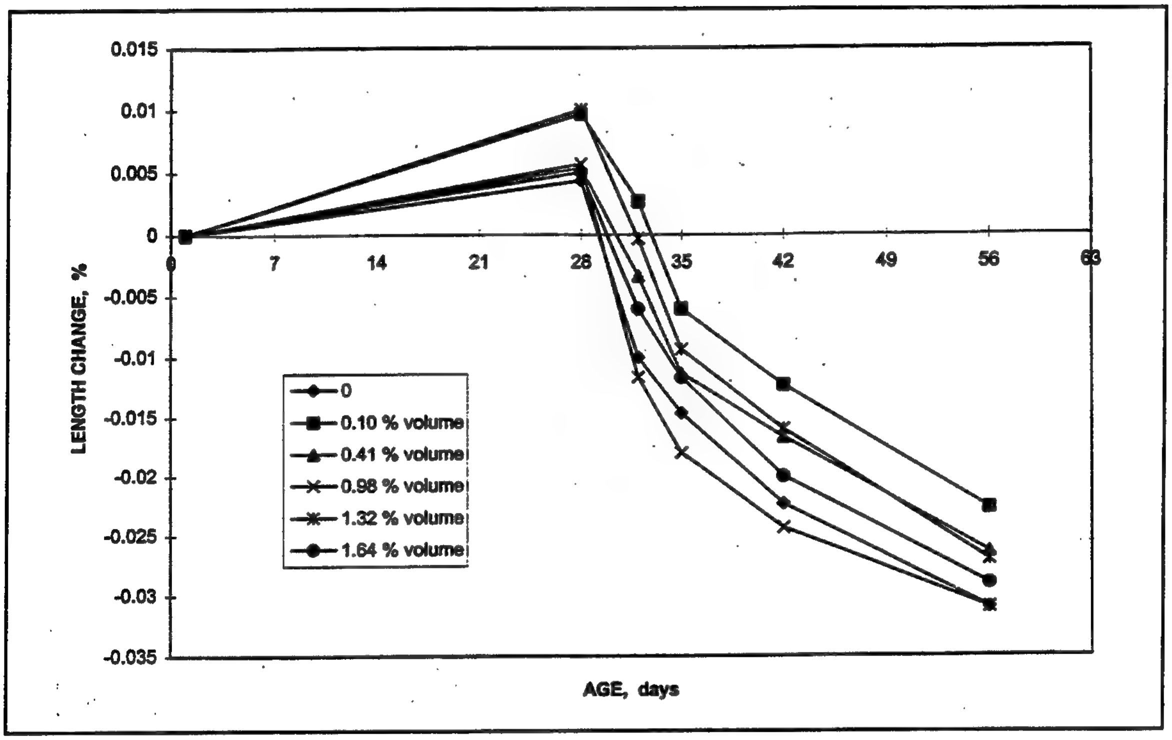

Figure 30. Drying shrinkage measurements

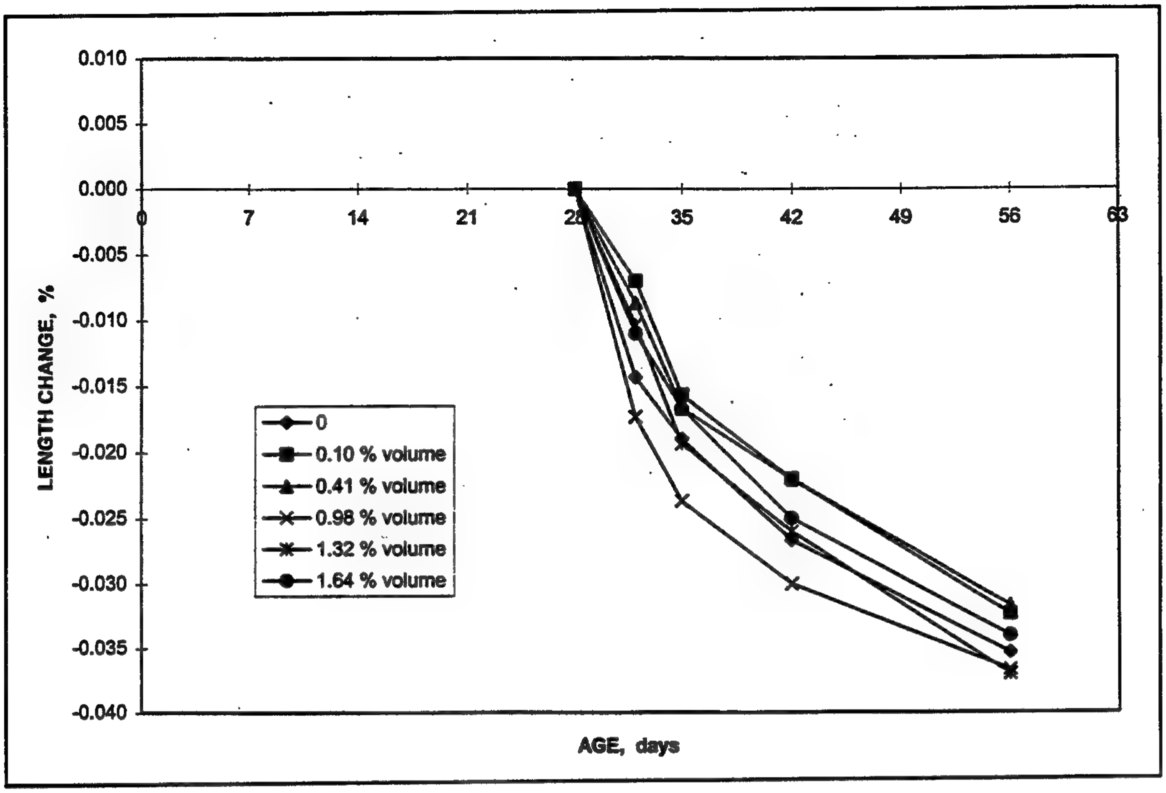

Figure 31. Drying shrinkage measurements normalized to zero at initiation of drying

4 Applications

General

As mentioned earlier in this report, Phase III of this investigation was to be a significant full-scale project capable of demonstrating the benefits of FRC with the Polyolefin fibers. At the time of writing of this report, several applications of Polyolefin FRC had been completed. Prior to the beginning of this investigation, the 3M Company participated in 16 projects where the Polyolefin fibers were used. Applications included whitetoppings, bridge decks, jersey barriers, and full-depth pavements. A summary is given in Table 8. Company brochures giving a brief description of some of these projects are included in Appendix D. Some of these projects are described by Ramakrishnan (1995). Since information about these projects is available elsewhere, minimal discussion will be provided below only as necessary to support the demonstration phase of this research. A description of 3M's commercialization efforts and the Phase III demonstration project is presented below.

3M Commercialization

3M began commercialization efforts 2 years prior to the beginning of this investigation. Development of the product began in-house in 1992 and continued in academia thereafter. The results from the investigation described in this report were intended to support and advance the private industry development and commercialization.

The Polyolefin fibers were developed for use in concrete. However, there are many potential applications for FRC in the construction industry. In an effort to define a focused market objective, 3M selected slab-on-grade application as the primary market objective. These applications were believed to afford the least liability risk for performance. This decision provided the guidance necessary for identifying which potential projects were of most interest for use within the parameters of the Construction Productivity Advancement Research (CPAR) Program Cooperative Research and

Table 8
Summary of 3M Demonstration Projects

Description	Date	Project Name	Location	Area (ft^2)	Thickness (in.)	Joint Spacing (ft)
Whitetopping	1993	Residential basketball court	Maplewood, MN	840	1.5	35 × 24 (no joints)
	1994	Bridge approach	Vivian, SD	3,000	3.5-4.5	4-50 × 14 (no joints)
	1995	Hwy I-295	Richmond, VA	4,200	2.0	3-100 × 14
	1995	Hwy 29	Charlottesville, VA	2,800	2.0	2-100 × 14
	1995	Hwy 169	Mankato, MN	1,260	3.0	8-6 × 6 4-12 × 6 2-12 × 12 2-12 × 15
	1996	Hwy LorRay Drive	Mankato, MN	64,000	3.0	5 × 6
	1996	Hwy 14	Fort Pierre, SD	28,000	2.5-3.5	14 × 50 14 × 500
Bonded Overlay	1994	Bridge deck	Vivian, SD	7,400	2.25	20 × 370
	1995	3M Tank farm 39	St. Paul, MN	1,080	1.5	18 × 60
Full Depth	1993	Residual driveway	Hugo, MN	860	1.5	24 × 36
	1994	Sheridan Lake Rd	Rapid City, SD	5,000	5.5	12 × 15
	1995	Hazardous waste trailer park (1)	3M Cottage Grove, MN	30,000	5.5	25 × 25
	1995	Bridge deck	Spearfish, SD	13,600	8.0	2-20 × 340
	1996	Dolly pads	3M Knoxville, IA	3,900	5.5	2-14 × 139 (no joints)
	1996	Hazardous waste park (2)	3M Cottage Grove, MN	30,000	5.5	25 × 25
	1996	Hwy 83	Oneida, SD	106,000	6.5/8.0	Various 1280' (no joints)

Note: To convert square feet into square metres, multiply by 0.09290304.
To convert inches into millimetres, multiply by 25.4.
To convert feet into metres, multiply by 0.3048.

Development Agreement (CRDA) contract with the USAEWES. While other types of applications have been pursued outside of the CPAR-CRDA, the primary market focus has continued to be slab-on-grade applications.

As part of the commercialization efforts, 3M made research data available to the public and private industry through personal contact, papers presented at technical conferences (ACI, American Society of Civil Engineers (ASCE), and Transportation Research Board (TRB), and technical literature. As a result of these commercialization efforts, significant Polyolefin FRC placements were completed in South Dakota, Minnesota, and Virginia through their respective state DOTs. The Phase III demonstration project described below was with the Mississippi DOT (MDOT). As projects were completed, case histories were prepared to provide an overall description of the project including early age performance. Videotapes documenting some of the research on a few of the projects were prepared. A summary of the information compiled by 3M prior to and during this research program is included in Appendix D.

Phase III Demonstration Project

Project selection

A pavement whitetopping was the preferred type of application for the demonstration project. While other types of slab-on-grade applications were considered, the properties of the Polyolefin FRC were judged to be particularly suited for whitetopping. After conclusion of the Phase I investigation, potential partners for the demonstration project were sought. Data, primarily from Phase I, were presented to members of the Research Department of MDOT. Having had a good experience with an ultrathin whitetopping (UTW) on a heavily trafficked intersection in 1995, the MDOT was interested in pursuing another whitetopping project using the Polyolefin fibers.

UTW's at intersections have proven to be good repair alternatives in several states (Mack, Cole, and Mohsen 1993; Speakman and Scott 1996). These UTW's have typically ranged from 50 to 125 mm (2 to 5 in.) in thickness and used sawed control joints at frequent intervals to ensure that drying shrinkage would not produce curling and warping stresses sufficient to debond the UTW from the existing hot-mix asphalt (HMA) pavement. Joint spacings generally followed the ratio of 12 to 1, i.e., a joint spacing of 12 mm (0.5 in.) for each 1 mm (0.04 in.) of slab thickness. This spacing factor applied to both transverse and longitudinal control joints. Indications were that the spacing factor could be significantly increased in whitetopping with the Polyolefin fibers (Ramakrishnan 1995). MDOT indicated an interest in pursuing a more aggressive whitetopping project than the previous intersection project in 1995. Additional discussions with members of the Mississippi Concrete Industries Association (MCIA) indicated interest from the private concrete industry in the Jackson, MS, area as well.

Funding. As a result of a proposal submitted to the Federal Highway Administration (FHWA) by MDOT, the project was selected for partial funding by FHWA under its Priority Technology Program (PTP). This program was established by the Intermodal Surface Transportation and Efficiency Act of 1991 to support innovative technology that would benefit from test installations. FHWA provided $100,000 in funding to this project for construction. MDOT sought a financial commitment from the private industry participants to provide for more active participation on their part and to encourage a commitment to quality. The local industry participants responded positively and agreed to provide their services at cost. The local concrete industry, through its trade association, MCIA, and the American Concrete Pavement Association also provided technical support in the areas of mixture proportioning, structural analysis, whitetopping design, and a trial placement. MDOT committed $25,000 in matching funds for construction, in addition to providing engineering support for preliminary structural analysis of the existing HMA pavement, overall project supervision, cold milling of the HMA pavement, traffic control during construction, monitoring of construction, and periodic post-construction condition surveys and performance evaluations. The total value of the MDOT services was estimated at $82,000. The USAEWES provided services for concrete mixture proportioning, quality assurance, structural analysis of the existing HMA pavement, whitetopping design, and post-construction performance evaluations. The value of the USAEWES services was estimated at $50,000. 3M also provided technical services for the use of their fibers, input to whitetopping design, and approximately 25 percent of the fibers at no cost.

Project extension. In return for the local concrete industry's commitment to the project, MDOT agreed to double the size of the test section to allow the industry an opportunity to evaluate options other than with the 3M Polyolefin fibers. The additional sections allowed the industry to include sections more conservative in design and deemed by the industry participants to carry less risk for premature failure. Also, since the Polyolefin fibers add considerable cost to the concrete, the additional sections would provide economic comparisons as well. This section will hereafter be referred to as the "MCIA section" and will only be briefly described in this report. Additional information describing the MCIA section has been presented by Crawley (1998). The initial test section, hereafter referred to as the "USAEWES section," was the focus of the Phase III demonstration project.

Site selection

As stated above, MDOT expressed an interest in a whitetopping application more aggressive than an intersection. The site recommended was a section of I-20 between Vicksburg and Jackson, MS. Originally constructed in 1967 and upgraded to interstate standards in 1972, the roadway in this area had required rehabilitation four times beginning in 1983 (Crawley 1998). The three rehabilitations since 1983 had been done to correct excessive rutting and

shoving of the HMA pavement. The high temperatures common to Mississippi during the summer months and the use of natural river gravel coarse aggregates cause the HMA pavement to be more prone to plastic flow, leading to rutting and shoving. Since many of MDOT's highways are constructed with HMA, rutting and shoving are a common problem statewide, especially on the interstate system and other four-lane highways frequented by heavy truck traffic. Therefore, MDOT has been seeking a solution that would minimize the frequency of required rehabilitations. A thin interstate whitetopping (TIW) was seen as an attractive option.

General criteria used by MDOT to identify a potential TIW project site were (a) structurally adequate thickness of HMA in place, (b) non-structural distress necessitating rehabilitation, and (c) sufficient traffic lanes to allow the closing of a lane during construction. Additional criteria specifically for this project were (a) pavement with severe rutting and/or shoving, (b) clear line of sight up to and through the work area to enhance safety, (c) nearby crossover for trucks, and (d) minimum 800 m (0.5 mile) clearance from any interchange. Several locations were discussed as possible candidates. Each of the above-mentioned seven criteria was satisfied at a location in the eastbound lane of the recommended site near mile marker 26 in Hinds County. At this location, I-20 is a divided, limited-access highway with two eastbound and two westbound lanes, each lane being 3.66 m (12 ft) in width. In each direction, a 3.05-m- (10-ft-) wide asphaltic concrete-surfaced shoulder borders the outside lane. Similarly, a 1.22-m- (4-ft-) wide asphaltic concrete-surfaced shoulder borders the inside lanes. The thickness of the in-place HMA was approximately 405 mm (16 in.), and a deflection survey indicated sufficient structural capacity. It was feasible to place all eastbound traffic on the median lane of the eastbound roadway during construction on the divided interstate facility. Ruts of up to 60 mm (2-3/8 in.) deep were common (Figures 32 and 33). The section was generally straight and flat, providing a clear line of sight and was more than 800 m (0.5 mile) from an interchange. A crossover could be made available to the frontage road on the south side of the interstate next to the eastbound lane.

MDOT provided an estimate of the average daily traffic (ADT) level of 7,311 for this section of the interstate. From this ADT estimate, a further estimate of the traffic level on the treated (low-speed) lane and the amount of truck traffic was made. These estimates of the volume of traffic on this section of I-20 are given in Table 9.

Table 9
Estimated Traffic Levels[1] for Test Section of I-20

Type of Vehicle	Average Daily Traffic
Cars	7,311
Trucks[2]	2,143

[1] Based on 1993 traffic data.
[2] Percentage of 29.31 total vehicle traffic estimated to be truck traffic.

Figure 32. Typical rutting of HMA pavement on I-20 at the site of whitetopping demonstration project

Figure 33. Closeup view of rutting

The climate in the Jackson, MS, area is warm and humid with long summers and short, mild winters. Figure 34 shows a plot of average temperature and precipitation data for Jackson. Temperatures average about 28 °C (about 82 °F) in July and about 9 °C (about 48 °F) in January. The average annual rainfall is approximately 1,370 mm (45 in.) and is relatively well distributed throughout the year. Small amounts of snowfall are possible in the winter months.

Pre-construction evaluation

The proposed demonstration project location was evaluated in April 1997, prior to any construction. This evaluation was a cooperative effort of MDOT and USAEWES and consisted of visual observation, coring and sawing of the pavement by MDOT, Dynamic Cone Penetrometer (DCP) testing by USAEWES, and non-destructive evaluation with a falling-weight deflectometer (FWD) by MDOT and a heavy-weight deflectometer (HWD) by USAEWES. The pavement distance evaluated was 762 m (2,500 ft), beginning at the western end of the test section. This evaluation was completed prior to the decision to extend the test section to 1,220 m (4,000 ft) in length. However, based on available historical information describing construction of the interstate and measurements from the evaluated section, it is reasonable to assume that the evaluated section should be representative of the entire 1,220-m (4,000-ft) test section.

Coring and sawing. A total of six cores were taken at various locations along the length of the planned demonstration project section, both in and out of the wheel paths. The cores were 100 mm (4 in.) in diameter and went the full depth of the pavement, including various layers of the existing HMA pavement and the underlying base-coarse material. The depth of the existing HMA was a minimum of 400 mm (16 in.), as shown in Table 10. The base coarse, consisting of a clay gravel, was about 203 mm (8 in.) deep, resulting in a minimum total pavement section thickness of 508 mm (20 in.). The subgrade was composed of low-plasticity silt. Some of the cores taken from the wheel paths indicated stripping in the lower half of the HMA. To determine whether the stripping actually existed or if it could have resulted from the coring operation, full-depth saw cuts were made to obtain blocks of the HMA for observation. No evidence of stripping was observed in these blocks of the HMA (Figure 35). Therefore, it was concluded that the HMA was sound throughout its depth and that the stripping observed in the cores was attributable to the washing action of the water used to cool the core barrel.

Dynamic-cone penetrometer (DCP). A DCP test was conducted in one of the core holes near the middle of planned test section to provide information on the strength of the existing subgrade. The pavement section in this area was 406 mm (16 in.) of HMA and 200 mm (8 in.) of granular base (clay gravel) over the existing subgrade. The DCP was driven to a depth of 928 mm (37 in.) through the pavement structure and into the subgrade. The DCP test

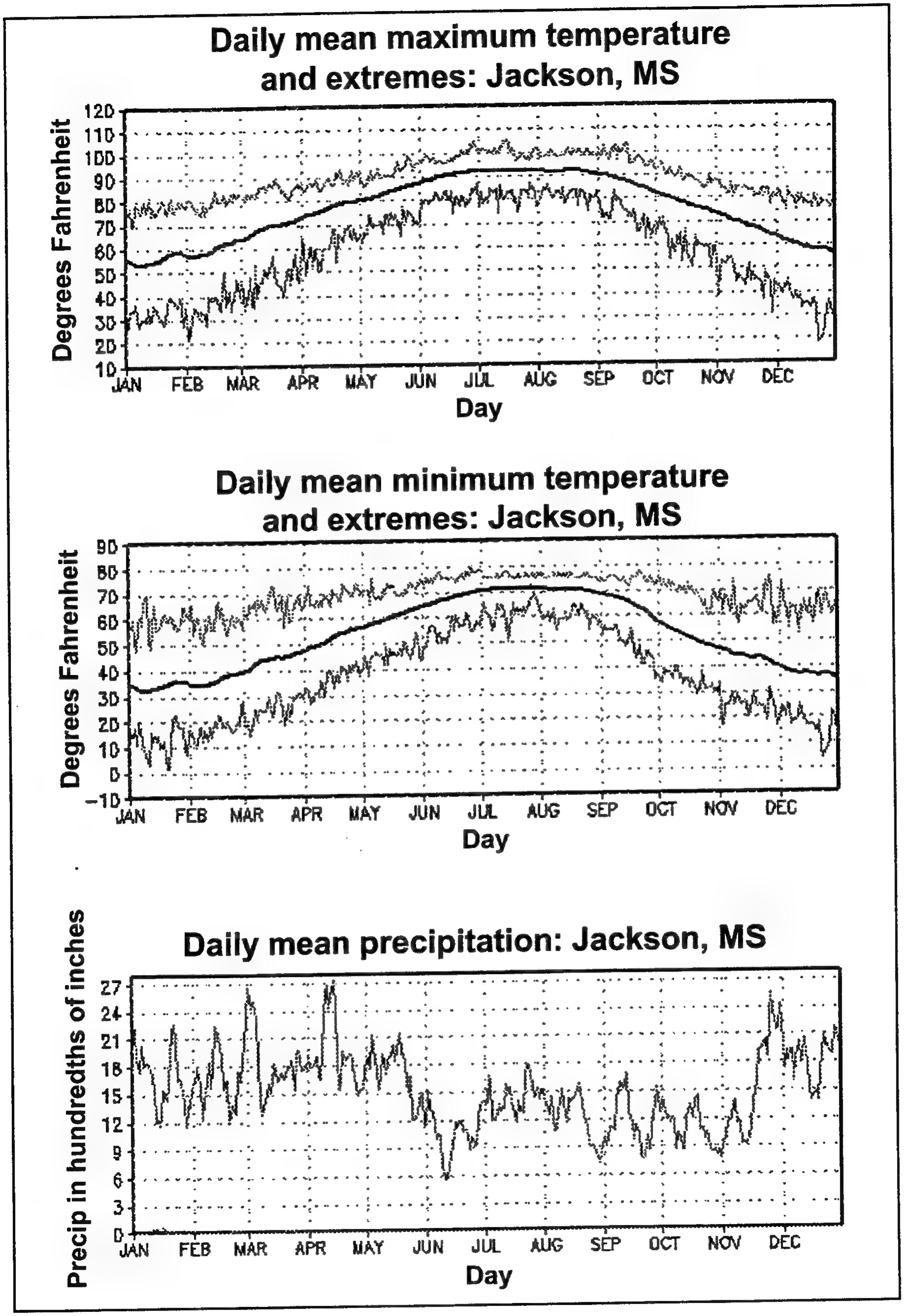

Figure 34. Climatic data for Jackson, MS

Table 10 Typical Initial Pavement Cross-Section Information[1]	
Material	Thickness, mm (in.)
Asphalt concrete	400 (16)
Base coarse	200 (8)
Subgrade	—

[1] Data from MDOT asphalt cores in the area and from previous MDOT data.

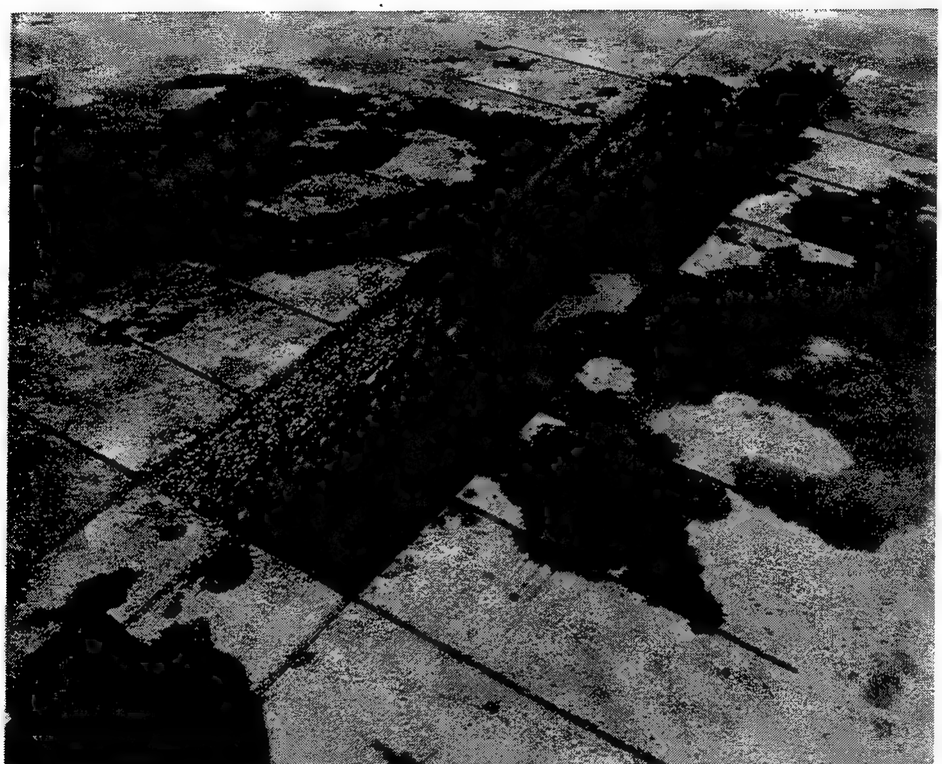

Figure 35. Blocks of HMA pavement sawed from I-20 at the site of the whitetopping demonstration project

results showed that the subgrade had a strength equivalent to an average California Bearing Ratio (CBR) value of 45 for about the first 152 mm (6 in.) of depth. This would account for the standard practice of compacting the top 152 mm (6 in.) of subgrade prior to the start of any construction. The strength decreased with further depth until at the final measurement at a depth of 928 mm (37 in.), the CBR value was at about 11. Figure 36 details the DCP test results.

Heavy-weight deflectometer (HWD). Two passes with an HWD was used to evaluate the stiffness of the existing pavement. The first evaluation pass was along the outside wheel path or rut, and the second pass was along the center of the traffic lane. The HWD performed a test at approximately 30-m (100-ft)

DCP TEST DATA

File Name: DCP

Project: *Interstate 20, Eastbound*
Location: Core Hole 7, STA 725+50
Date: 30-Apr-97
Soil Type(s): AASHTO A-4 / A-5

Hammer
- ● 10.1 lb
- ○ 17.6 lb
- ○ Both hammers used

Soil Type
- ○ CH
- ○ CL
- ● All other soils

No. of Blows	Accumulative Penetration (mm)	Type of Hammer
0	439	2
5	458	2
12	488	2
25	542	2
10	571	2
10	597	2
10	622	2
10	650	2
10	673	2
10	700	2
10	729	2
10	758	2
10	796	2
5	826	2
4	847	2
3	871	2
3	900	2
3	928	2
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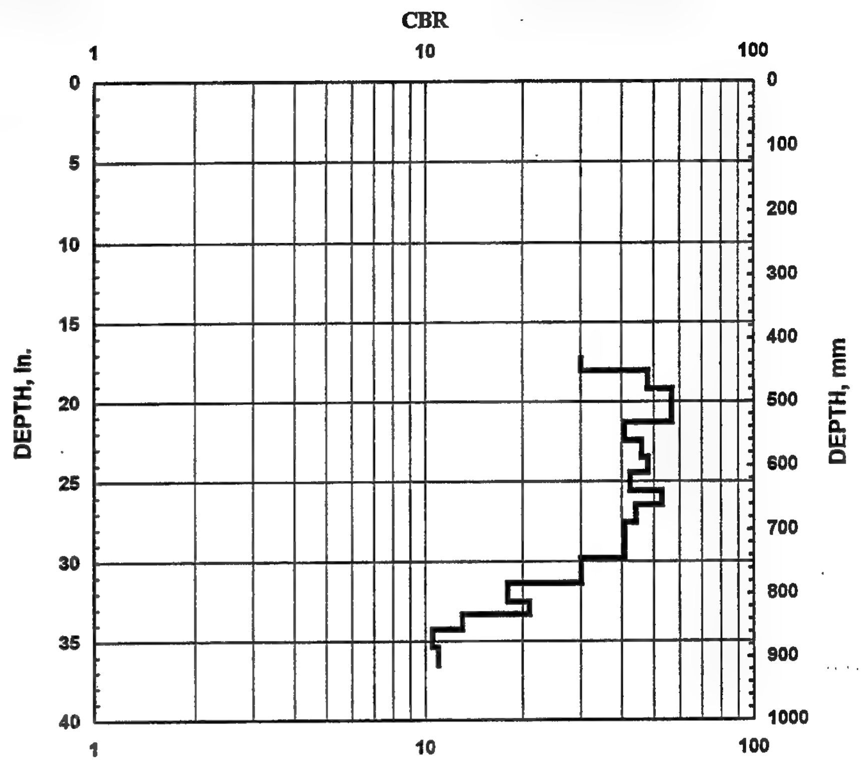

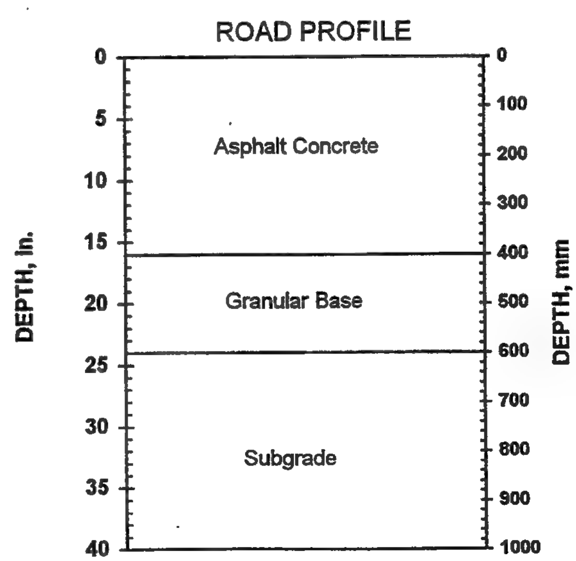

Figure 36. DCP test data

intervals, for each of the two passes along the test section. The impulse stiffness modulus (ISM) values in and out of the wheel paths were similar at a given linear location. The ISM values are determined at each test location by using the force or load applied to the pavement at that location divided by the deflection measured at the center of the load. As shown in Figure 37, the ISM values from the middle of the traffic lane prior to construction varied from a low of about 175 MN/m (1,000,000 lbf/in.) to a high of about 438 MN/m (2,500,000 lbf/in.). The average ISM for the entire demonstration project section was approximately 302 MN/m (1,725,000 lbf/in.).

The average deflection under an average applied load of over 71.2 kN (16,000 lbf) was 0.24 mm (9.45 mils) (Table 11). Results from the FWD tests conducted by MDOT gave similar results. From the FWD, the average deflection under a 40 kN (9,000 lbf) was 0.21 mm (8.15 mils), with a back calculated modulus (using MODULUS v.5.0) of 2,365 MPa for the HMA, 148 MPa for the granular base-coarse material, 155 MPa for the granular subbase, and 118 MPa for the subgrade (Crawley 1998).

Table 11
Deflection Results of HWD Testing

Date Evaluated	Feature	Load		Deflection	
		Mean kN (lbf)	Std Dev N (lbf)	Mean, mm (mil, in./1,000)	Std Dev, mm (mil, in./1,000)
4/29/97	Entire section[1]	71.7 (16,117)	1,414 (318)	0.240 (9.45)	0.0434 (1.708)
9/19/97	200 mm PCC[2]	88.7 (19,929)	3,336 (750)	0.184 (7.26)	0.0192 (0.754)
	150 mm PCC	87.5 (19,668)	2,998 (674)	0.210 (8.25)	0.0033 (0.129)
	150 mm Fibrous	86.3 (19,410)	538 (121)	0.200 (7.87)	0.0356 (1.400)
	100 mm Fibrous	87.1 (19,582)	2,447 (550)	0.209 (8.24)	0.0294 (1.158)
1/25/98	200 mm PCC	88.8 (19,974)	1,250 (281)	0.217 (8.55)	0.0135 (0.532)
	150 mm PCC	88.0 (19,782)	2,037 (458)	0.208 (8.18)	0.0279 (1.099)
	150 mm PCC	87.4 (19,639)	641 (144)	0.194 (7.64)	0.0394 (1.553)
	100 mm Fibrous	86.6 (19,474)	1,984 (446)	0.175 (6.88)	0.0251 (0.990)

[1] Tested 762 mm (2,500 ft) of total section length of 1,219 m (4,000 ft). Demonstration section adjusted after the initial testing was completed.
[2] PCC = portland-cement concrete.

The deflection survey and subsequent analysis indicated that the overall structural integrity of the pavement section was structurally sound and adequate for the current traffic load. Previous investigations of the same pavement structure in nearby areas by MDOT had revealed that the rutting and shoving experienced at the surface were the result of dilatation caused by shearing stresses near the surface of the HMA, and not by displacement or shear failure in the base coarse or subgrade materials.[1] Therefore, it was concluded that the

[1] Personal Communication, 1997, A. B. Crawley, Research Engineer, Mississippi Department of Transportation, Jackson, MS.

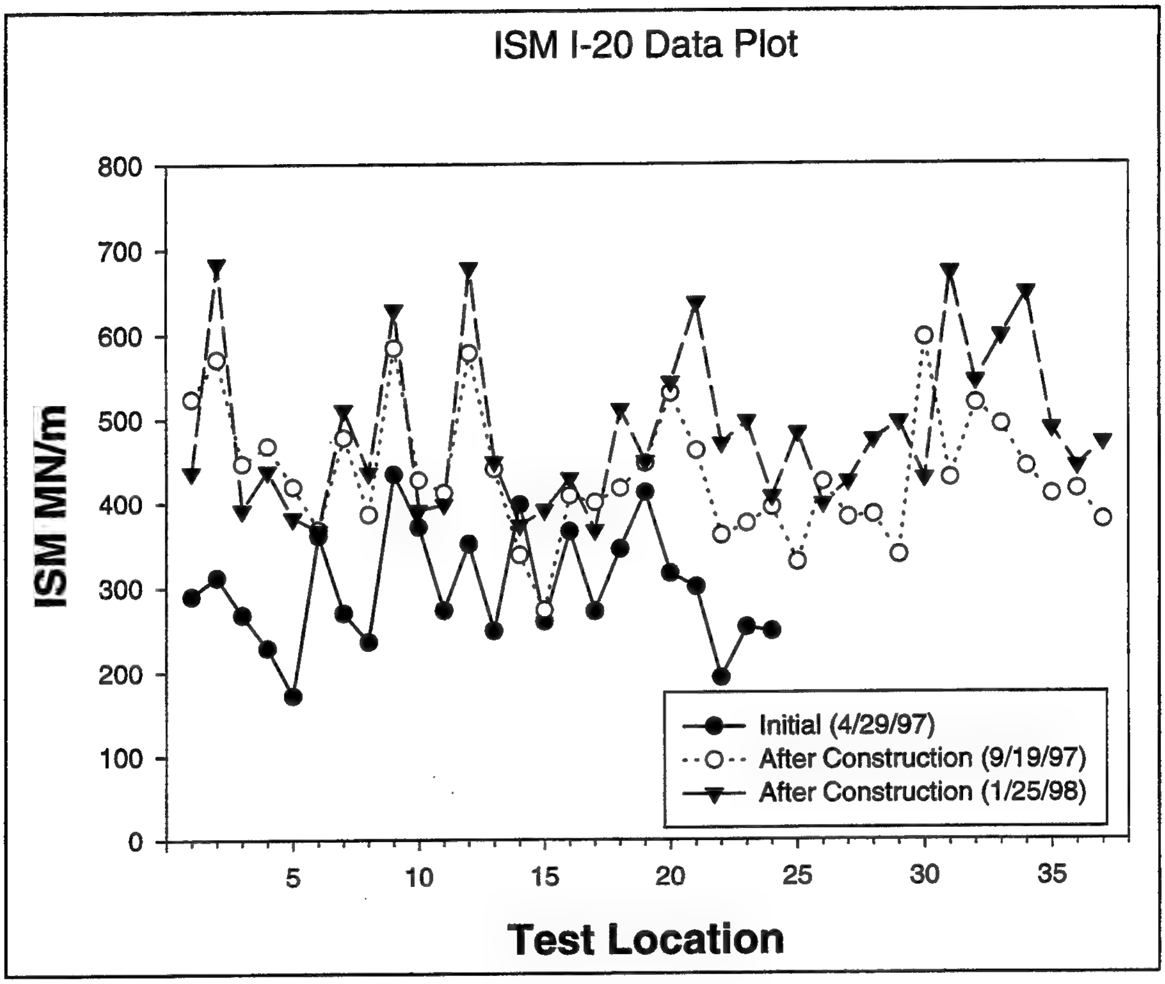

Figure 37. ISM values prior to and after construction

existing pavement section was structurally adequate for a thin whitetopping application.

Whitetopping design

Available design procedures. Two available software design packages were used by MCIA personnel to establish a baseline design:

a. PCAPAV (American Concrete Pavement Association (ACPA) 1990).

b. Pavement Analysis Software (PAS) (ACPA 1993).

Input parameters for these two design procedures are given in Table 12. Recommended whitetopping design thicknesses from the PCAPAV program ranged from 152 to 279 mm (6.0 to 11.0 in.) for various combinations of load transfer and shoulders. Recommended thicknesses from the PAS program ranged from 216 to 298 mm (8.5 to 11.75 in.) for different values of resilient modulus and reliability requirements.

Table 12
Input Parameters for PAS and PCAPAV Whitetopping Design Procedures

AADT = 7,311
ADTT = 2,143
K = 3.45 MPa
Design life = 20 years
Load safety factor = 1.0
Modulus of rupture = 4.48 MPa
Doweled and aggregate interlock for joints
Concrete shoulder and no concrete shoulder

In addition to the two procedures mentioned in the paragraph above, a new preliminary mechanistic design procedure for UTW was considered by USAEWES personnel as a means to provide input for selection of control joint spacings. This procedure, as described by Mack et al. (1997), was developed from performance surveys of UTW pavements and a finite-element-based analytical study. Prediction algorithms were developed for stresses and strains caused by both temperature and traffic loadings. Two types of pavement failure were considered: (a) fatigue of the portland-cement concrete and (b) fatigue of the HMA under joint loading. The algorithms presented by Mack et al. (1997) were implemented in a personal computer spreadsheet. Representative material properties were selected, and the traffic cases considered were identical to those used in the PCAPAV analyses. The resulting joint spacings varied from 940 to 1,350 mm (37 to 53 in.), depending upon the traffic and the assumed modulus of rupture of the FRC. Because the

I-20 TIW was thicker than traditional UTW pavements, these joint spacings were considered to be overly conservative and at best represent a lower bound to the required control joint spacing.

These thick whitetopping recommendations and close control joint spacings were generally expected from the design procedures. Neither procedure takes into account the influence of the expected bond between the concrete and the HMA and subsequent load transfer through the HMA. Since one of the project requirements was a substantial and structurally sound HMA pavement to accept the TIW, given adequate bond, it was reasonable to expect that considerable load would be transferred through the existing HMA pavement. Additionally, neither program takes into account the full influence of the fibers on the hardened properties of the concrete. Each program essentially designs a concrete pavement assuming the hardened properties of concrete without fibers, and that all load must be carried by the concrete pavement. The proposed TIW fits neither situation. However, these being the only known design programs available at the time, it was determined that their recommendations would establish a point of reference from which the eventual TIW could be compared. Consequently, the TIW thickness and control joint spacing were based on results of other thin and ultra-thin whitetopping projects completed since 1992.

TIW design. Several UTW's with thicknesses ranging from 64 to 100 mm (2.5 to 3.9 in.) had been constructed by the South Dakota DOT in 1995 and 1996 (Ramakrishnan 1995, 1996). No major deficiencies had been found within the short service life. Only a few corner cracks had become evident in areas where the thickness and structural integrity of the HMA beneath the UTW was less than desirable. Even so, the cracks had shown no evidence of widening. There was, however, one significant difference between the UTW's in South Dakota and the proposed TIW on I-20 that caused concern about the thin sections. The traffic conditions, both volume and loading, were considerably higher on I-20 than was the case on either of the applications in South Dakota. On the other hand, one positive aspect of the I-20 site was that the HMA had adequate thickness, was structurally sound, and was capable of considerable load transfer. It was reasoned that the minimum thickness for the TIW on I-20 using FRC with the Polyolefin fibers should be 89 mm (3.5 in.).

Ultimately, the condition of the existing HMA on I-20 dictated the actual thickness. Inspection of the HMA cores and blocks indicated that the area of HMA conducive to plastic flow during the hot summer months was primarily the top 89 mm (3.5 in.) of the pavement. It was deemed prudent to remove all of this material prior to placement of the TIW. To ensure all of the poor HMA material was removed, the minimum milling and inlay thickness was specified to be 100 mm (3.9 in.) for the USAEWES section, and 150 and 200 mm (5.9 and 7.9 in.) for the industry section.

Another priority in the design of the TIW was economic competitiveness. As a general rule, initial costs for construction of a concrete pavement are higher than for an HMA pavement. The same is true when comparing a

whitetopping to a thin HMA overlay. While it is anticipated that the TIW will prove to be more cost effective on a life-cycle basis, it was still necessary to construct the TIW as economically as possible. Thinner sections result in lower construction costs primarily due to savings in the volume of concrete required. Additional savings can also be realized in other areas of the construction. Another competitive requirement was the time required for lane closure. It was desired that the TIW be opened to traffic within 30 hr after placement.

The test section was located on approximately 1,220 m (4,000 ft) of pavement in the outside (low-speed) lane of the eastbound roadway beginning between the 25 mile (40.2 km) and 2.6 mile (41.8 km) markers. The test section was divided approximately in half, with one-half being designated as the MCIA section and the other half being designated as the USAEWES section. Beginning at the western end of the test section, the first 605 m (1,985 ft) was designated as the MCIA section. This section included three different TIW designs for evaluation. The first design was portland-cement concrete (PCC) without fibers, 153 m (502 ft) long and 200 mm (7.9 in.) thick. Transverse control joints were sawed at 3.65-m (12-ft) intervals. The second design was PCC without fibers, 135 m (443 ft) long and 150 mm (5.9 in.) thick. Transverse and longitudinal control joints were sawed at 1.82-m (6-ft) intervals. The third design was fibrillated polypropylene FRC with 1.8-kg/m^3 (3.0-lb/yd^3) fiber loading. The section of fibrillated FRC was 317 m (1040 ft) long and 150 mm (5.9 in.) thick. Transverse and longitudinal control joints were sawed at 1.82-m (6-ft) intervals. A general layout of the MCIA section in shown in Figure 38. The second 614-m (2,014-ft) section, designated as the USAEWES section, was 100 mm (3.9 in.) thick throughout. The concrete was an FRC with 14.9 kg/m^3 (25 lb/yd^3) of Polyolefin Type 50/63 fiber. The primary variable was spacing of the control joints. A section 164 m (538 ft) long received transverse control joint spacings of 7.6 m (25 ft). A section 292 m (958 ft) long received transverse control joint spacings of 4.6 m (15 ft). A section 122 m (400 ft) long received transverse control joint spacings of 12.2 m (40 ft). A section 37 m (120 ft) long received transverse and longitudinal control joint spacings of 1.82 m (6 ft). A general layout of the USAEWES section is given in Figure 39.

The specification for this project was written by a committee including representatives from MDOT, USAEWES, MCIA, 3M, the paving contractor, concrete suppliers, and one of the portland-cement suppliers. Special provisions were made where deemed necessary for this project. However, MDOT requested that the specification be written such that with minimal revisions, it could be used for other TIW projects statewide.

The committee members recognized that the TIW design was outside the accepted engineering boundaries for thickness and control joint spacing, especially for the USAEWES section. However, being encouraged by the performance of similar sections constructed by the South Dakota DOT (SDDOT), the committee desired to design a test section which would

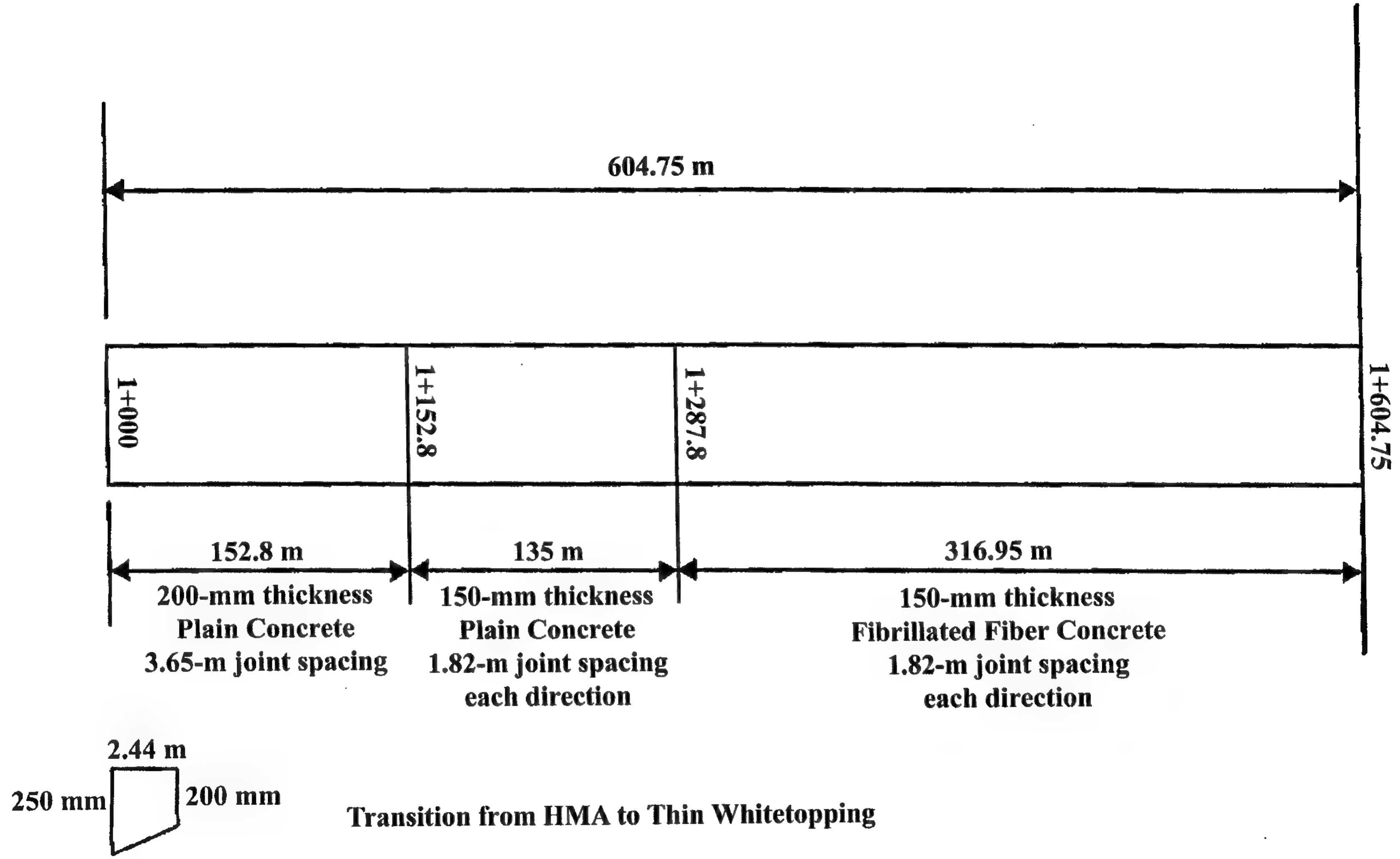

Figure 38. MCIA whitetopping section

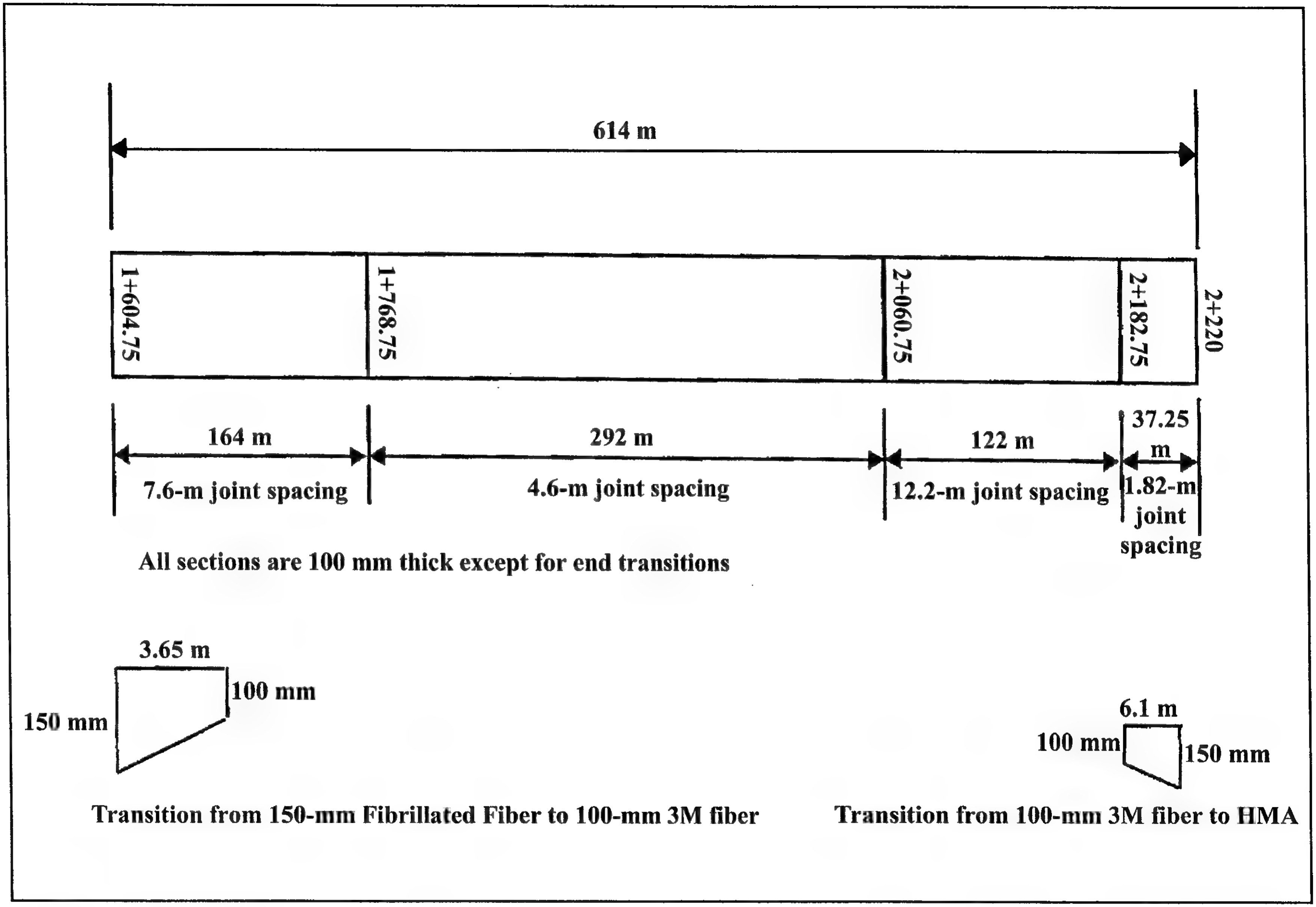

Figure 39. USAEWES whitetopping section

provide information indicating whether the hardened properties enhancements given to the concrete by the Polyolefin fibers could justify the thinner overlay and wider control joint spacings.

Concrete mixtures

The requirements for the concrete mixtures are given in Table 13. Mixtures for the MCIA section were proportioned by the concrete suppliers. Mixture proportions are given by Crawley (1998). The Polyolefin mixtures were proportioned by USAEWES. A general description of the materials, mixtures, and test results from the trial batches is given below.

Table 13
Concrete Mixture Specifications

Slump
Air content - 3 to 6 percent
Yield - ±3 percent
Compressive strength - 17 MPa @ 30 hr (Target) 25 MPa @ 14-days (Required)

Materials. None of the materials were common to the two concrete producers; therefore, different mixture proportions were required for each producer. Listings of the materials for producer A and producer B are given in Tables 14 and 15, respectively. Material test reports are given in Tables B12-B17, Appendix B.

Mixtures and test results. The combination of the target specification requirement of 17 MPa at 30 hr, an approximate hauling time of 40 min, and daytime ambient temperatures above 35 °C (95 °F) made it difficult to proportion a mixture that would have adequate workability at the time of placement. The low w/(c+m) necessary to meet the strength requirement resulted in high cementitious material contents. The high cementitious material contents facilitated a rapid loss of workability in the high temperatures. In efforts to meet the requirements, various combinations of portland-cement and fly-ash quantities, w/(c+m), and water-reducing admixtures were evaluated. In order to meet project specifications at the placement site, it was necessary to proportion the mixtures such that initially both the slump and air contents were high. Thirteen mixtures were proportioned and tested using materials from producer A, and twenty-two mixtures were proportioned and tested using materials from producer B. Test results from these mixtures are summarized in Table 16. To simulate the high ambient and concrete temperatures, the materials were stored in a variable temperature room set at approximately 32 °C (90 °F) for many of the trial mixtures. The initial mixing was also carried out in the high temperature and held in the mixer for 40 min to monitor the loss of workability. Three mixtures for each producer were verified in

Table 14
Materials Used by Producer A

Material	Description
Portland cement	Type I
Fly ash	Class C
Fine aggregate	Natural siliceous sand
Coarse aggregate	25.0-mm NMS natural gravel
Air-entraining admixture	
Water-reducing admixture	Type A; normal
Water-reducing admixture	Type A; mid-range
Fibers	3M Polyolefin Type 50/63

Table 15
Materials Used by Producer B

Material	Description
Portland cement	Type I
Fly ash	Class F
Fine aggregate	Natural siliceous sand
Coarse aggregate	25.0-mm NMS natural gravel
Air-entraining admixture	
Water-reducing admixture	Type A; normal
Water-reducing admixture	Type A; mid-range
Fibers	3M Polyolefin Type 50/63

Table 16
Whitetopping Trial Mixtures

Mixture No.	w/(c+m)	F/C, % volume	Mortar Content m	Paste/ Mortar	Slump, Initial mm	Slump, 30 min. mm	Air, Initial %	Air, 30 min. %	Unit Weight, Initial kg/m	Unit Weight, 30 min kg/m	Yield, 30 min m	Temp, °C	Compressive Strength 24 hr MPa	24 hr acc. MPa[3]	30 hr MPa	30 hr acc. MPa[3]	7-day MPa
Producer B																	
B1	0.36	20	0.6785	0.5800	95		7.2		2,183			26.7	13.6				24.3
B2	0.32	20	0.6472	0.6400	45	40	3.5		2,250		0.985	26.7	18.7				31.2
B3	0.32	20	0.6587	0.6400	70	40	4.0		2,230		0.991	26.7	18.0				30.9
B4	0.29	20	0.6457	0.6200	40	30	4.6	3.6	2,229	2,261	0.991	26.1	21.1				34.7
B5	0.30	20	0.6250	0.6500	40	15	4.3	3.3	2,242	2,271	0.983	26.1	19.9				36.3
B6	0.34	20	0.6354	0.6000	100	55	7.3	4.9	2,158	2,219	1.002	26.1	17.1	19.9			32.7
B7	0.31	25	0.6031	0.65	135	100	9.2	6.3	2,119	2,190	1.017	26.1	14.0	15.3			28.2
B8[1]	0.30	20	0.5912	0.66													
B8[2]	0.30	20	0.6171	0.61	25	0	4.5	33		2,276	0.982	38.9	25.1				
B9	0.33	20	0.5913	0.67	185	115	9.7	5.7	2,090	2,184	1.016	30.0	11.2	16.7			27.6
B10	0.33	20	0.5848	0.66	135	95	7.3	4.4	2,154	2,219	1.002	30.0	14.8	19.8			32.0
B11	0.30	20	0.6171	0.61	70	40	5.7	3.7	2,209	2,268	0.991	30.0	17.7	22.9			34.5
B12[1]	0.32	20	0.5853	0.67													
B12[2, 4]	0.31	20	0.5828	0.67		50		3.4		2,259	0.993	36.1	19.8	20.7			
B13	0.33	20	0.6005		mix not done												
B14	0.36	15	0.5818	0.63	125	25	5.6	3.3	2,187	2,268	0.987	33.6		16.3	15.2	20.4	
B15	0.36	15	0.5812	0.64	100	40	2.9	1.9	2,248	2,290	0.976	33.0		17.3	16.3	21.3	
B16	0.37	15	0.5876	0.64	170	30	9	3.2	2,080	2,245	0.993	33.9					29.5
B17[1]	0.34	20	0.5905	0.66													
B17[2]	0.37	20	0.5679	0.66		55		3.9		2,203		34.4	13.2	16.0	15.5	17.1	

(Continued)

[1] As proportioned.
[2] As batched in ready-mix truck.
[3] Cured at 37.8 °C.
[4] In ready-mix truck for trial placement.

Table 16 (Concluded)

Mixture No.	w/(c+m)	F/C, % volume	Mortar Content m	Paste/ Mortar	Slump, Initial mm	Slump, 30 min mm	Air, Initial %	Air, 30 min %	Unit Weight, Initial kg/m	Unit Weight, 30 min kg/m	Yield, 30 min m	Temp, °C	Compressive Strength				
													24 hr MPa	24 hr acc. MPa[3]	30 hr MPa	30 hr acc. MPa[3]	7-day MPa
B18	0.35	20	0.5848	0.67	90	25	6.1	3.1	2,203	2,261	0.982	34.7		16.5	17.4	18.8	
B19[1]	0.39	15	0.5696	0.67													
B19[2]	0.39	15	0.5696	0.67	195	145	12.3	12.2	2,056	2,056	1.078	32.8					
B20	0.38	15	0.5682	0.67	205	100	6.4	4.8	2,109	2,213	1.002	33.3					
B21	0.35	20	0.5701	0.69	mix not done										28.0		
B22	0.37	15	0.5703	0.67	165	70	8.3	3.9	2,105	2,244	0.991	29.7					
							Producer A										
A1	0.32	20	0.6587	0.64	100	85	10.0	4.9	2,111	2,235	0.993	26.7	15.5				
A2	0.34	20	0.6467	0.62	140	85	10.5	5.9	2,087	2,200	1.009	26.1	13.5	16.7			29.8
A3	0.32	20	0.6472	0.64	100	55	9.5	4.7	2,119	2,229	0.998	26.1	15.1	19.9			32.0
A4	0.30	25	0.6002	0.64	160	55	14.0	6.0	2,015	2,209	1.017	26.1	12.7	15.4			28.8
A5	0.31	20	0.5912	0.64	85	65	3.3	3.0		2,266	0.989	39.4	16.2				
A5[2,4]	0.28	20	0.5851	0.63													
A6	0.30	20	0.5882	0.65	160	85	14.6	9.5	1,976	2,132	1.055	28.9	9.8	15.4			25.9
A7	0.30	20	0.5882			mix not done											
A8	0.31	20	0.5996			mix not done											
A9	0.33	15	0.5843	0.62	190	100	15.2	6.5	1,954	2,235	1.012	32.9		18.7	16.8	19.2	
A10	0.33	15	0.5881	0.61	160	40	12.6	4.2	2,021	2,258	1.002	33.7		18.3	16.4	20.1	
A11	0.34	15	0.5814	0.61	165	65	11.7	3.6	2,028	2,274	0.993	32.8		17.8	15.6	20.1	
A11[2]	0.34	15	0.5814	0.61	0		4.1		2,302			34.3	13.6	14.6	15.8	16.3	
A12[2]	0.35	15	0.5817	0.62	100	80	6.2	4.4	2,229	2,249	1.001	36.7					
A13	0.34	15	0.5801	0.62	160	100	11.2	7.7	2,069	2,176	1.038	29.8					

1.5- or 2.3-m^3 (2- or 3-yd^3) batches in truck mixers. Mixture A13 was ultimately selected for use at producer A, while mixture B22 was selected for use at producer B. Mixture proportions are given in Table 17.

Table 17
Mixture Proportions for USAEWES Whitetopping Test Section

Material	SSD Batch Mass, 1 m^3	
	Producer A	Producer B
Portland cement	415	427
Class C fly ash	63	0
Class F fly ash	0	58
Fine aggregate	573	479
Coarse aggregate	1,029	1,058
Type 50/63 fibers	14.85	14.85
Water	164	185
Air-entraining admixture	0.12 ℓ	0.12 ℓ
Normal water-reducing admixture	2.17 ℓ	2.84 ℓ
Mid-range water-reducing admixture	1.86 ℓ	1.86 ℓ

Construction

Milling. MDOT began the construction sequence on Monday, 18 August 1997, with the erection of signs necessary to slow and redirect traffic to the median lane. Milling began the following day. The original plan called for the USAEWES section to begin at the western end of the test section. However, MDOT made a last-minute change and reversed the two sections, resulting in the MCIA section beginning at the western end of the test section. The USAEWES section now began at the midpoint of the test section and continued to the eastern end. At the beginning of the MCIA section, the milling depth was 250 mm (9.8 in.) and gradually transitioned to 200 mm (7.9 in.) over a distance of 2.44 m (8 ft). This was done to provide additional strength at the point of transition from the HMA to the TIW. At the beginning of the USAEWES section, the milling depth was 150 mm (5.9 in.) and gradually transitioned to 100 mm (3.9 in.) (Figure 40) over a distance of 3.65 m (12.0 ft). Since a cold joint with no dowels to transfer load across the joint would separate the MCIA and USAEWES sections, the additional depth should provide additional strength at the point of transition. At the end of the USAEWES section, the milling depth was gradually increased again to 150 mm (5.9 in.) to provide additional strength at the point of transition from the TIW to the HMA. These transition areas are detailed in Figures 32 and 33 for the MCIA and USAEWES sections, respectively. Milling was completed on Friday, 22 August 1997. An accident in the MCIA section over the weekend resulted in a considerable quantity of diesel fuel being spilled into the milled area. As a result, additional milling was required in this area on

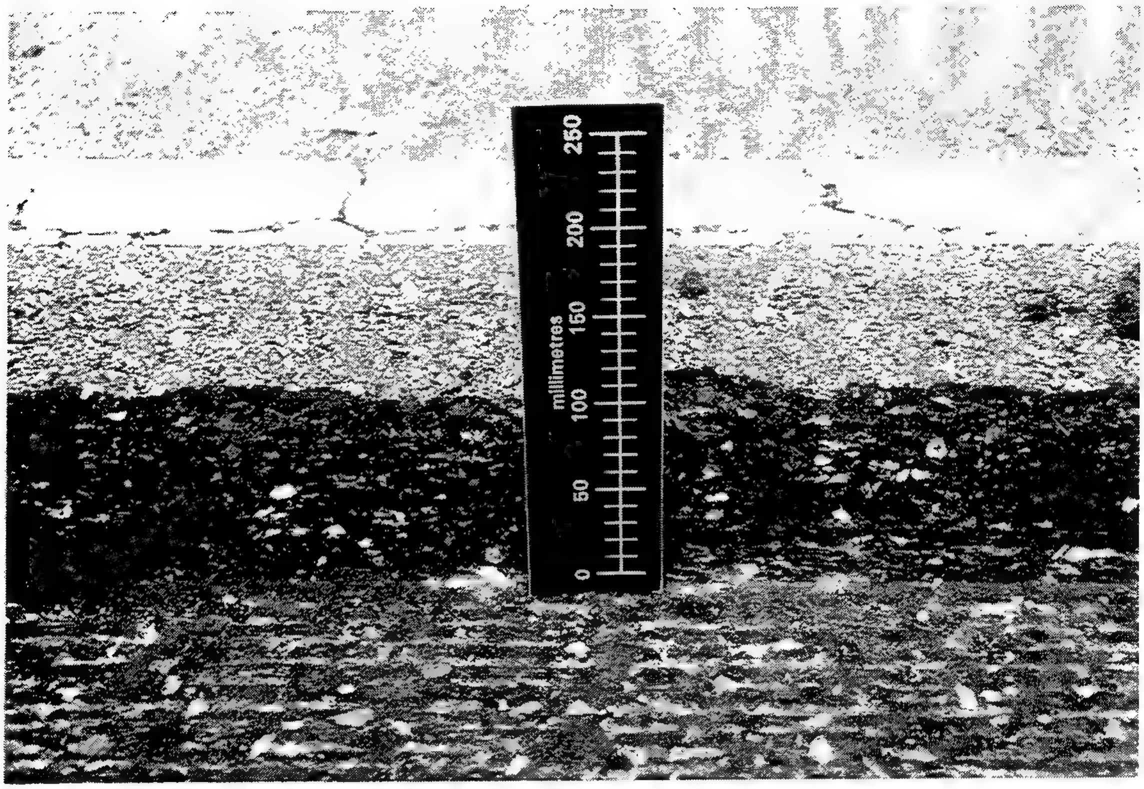

Figure 40. Milling depth on USAEWES whitetopping test section

Monday, 25 August 1997, to remove the contaminated HMA. An additional 7 to 13 mm (0.3 to 0.5 in.) was milled from the contaminated area.

Concrete placement. Concrete placement began in the MCIA section at approximately 0600 hr on Tuesday, 26 August 1997. A description of the placement is given by Crawley (1998). Concrete placement in the USAEWES section began at approximately 0630 hr on Wednesday, 27 August 1997. The early start was to take advantage of the cooler morning temperatures. The production and delivery of concrete were arranged such that each of the two concrete producers had 12 trucks of 7.6-m^3 (10-yd^3) capacity each dedicated to the project. The batch size was 6.1 m^3 (8 yd^3). Concrete delivery alternated between the two producers. The first 12 deliveries were from producer A. This producer used a conventional dry-batch plant. All mixing was done in the truck mixers. The Polyolefin fibers were added to the truck mixer after all other materials had been batched and mixed for a period of time. At the start of the placement, both the slump and air content were less than desired. The air content did not meet project specification. It was also noted that some of the Polyolefin fibers were not adequately distributed. Adjustments were made to the water and AEA contents at the batch plant, which improved the mixtures. However, the air content continued to be borderline in meeting project specifications, and a few fiber balls and unopened Polyolefin fiber bundles continued to be noted.

Producer B's first delivery was batch number 13. This producer used a central mixing plant to mix the concrete without fibers. After the mixed concrete had been discharged into a truck mixer, the fibers were added to the concrete in the truck mixer. Additional mixing was done in the truck mixer to distribute the Polyolefin fibers. Approximately 8 to 10 min of additional mixing in the truck mixer was required to fully distribute the fibers. The mixtures met project specifications at the placement site, and the Polyolefin fibers appeared to be well distributed.

Producer A's second and final round of deliveries began with batch number 25. An adjustment in the batching sequence provided for additional mixing time at the batch plant for the concrete both before and after addition of the Polyolefin fibers. This adjustment resulted in a significant improvement in the concrete properties as delivered to the project site. All deliveries to the project site during this round met project specifications for slump and air content. In addition, distribution of the fibers appeared to be improved.

Producer B's second and final round of deliveries began with batch number 37. Again, the mixtures met project specifications at the placement site, and the Polyolefin fibers appeared to be well distributed. The placement was completed at approximately 1300 hr with a total of approximately 260 m^3 (340 yd^3) of concrete being placed. Initial estimates for the volume of Polyolefin FRC were approximately 226 m^3 (296 yd^3). This additional usage of 34 m^3 (44 yd^3) is a larger variance (15 percent) than is commonly expected. Possible reasons for this are discussed in Chapter 5.

The delivery rate was such that concrete was maintained in front of the slip-form paver at all times (Figures 41 and 42). Concrete slumps at the paver ranged from 40 to 95 mm (1.5 to 3.75 in.). While all mixtures were easily placed and consolidated by the paver, it was observed that mixtures having a slump of approximately 50 mm (2 in.) appeared to be optimum (Figure 43). Lower slump mixtures resulted in the top surface of the pavement having a somewhat torn appearance out of the paver. Higher slump mixtures tended to be somewhat spongy. Nevertheless, the appearance of the surface out of the paver was generally good (Figure 44). Except for the first 12 batches delivered (low slump and low air), the effort required for hand-finishing steps was generally typical of that required for concrete without fibers. A 3-m (10-ft) straight edge was used to finish the surface on all but the first 12 batches. Because of the more torn surface with the first batches, a bull float was used to better close and smooth the surface. As would be expected, use of the bull float rather than the straight edge in this area resulted in a less flat surface. A burlap drag was used throughout to texture the surface of the pavement (Figure 45). After the burlap drag, a white-pigmented curing compound was used to retard evaporation of water from the surface (Figure 46). Control joints were cut using soft-cutting techniques.

Quality control. Quality-control testing for the USAEWES section was performed by USAEWES personnel. Acceptance testing was performed at

Figure 41. FRC discharged in front of slipform paving machine on USAEWES whitetopping test section

Figure 42. FRC entering slip-form paving machine on USAEWES whitetopping test section

Figure 43. Typical slump of polyolefin FRC placed in USAEWES whitetopping section

Figure 44. FRC as placed by a slipform paving machine on the USAEWES whitetopping test section

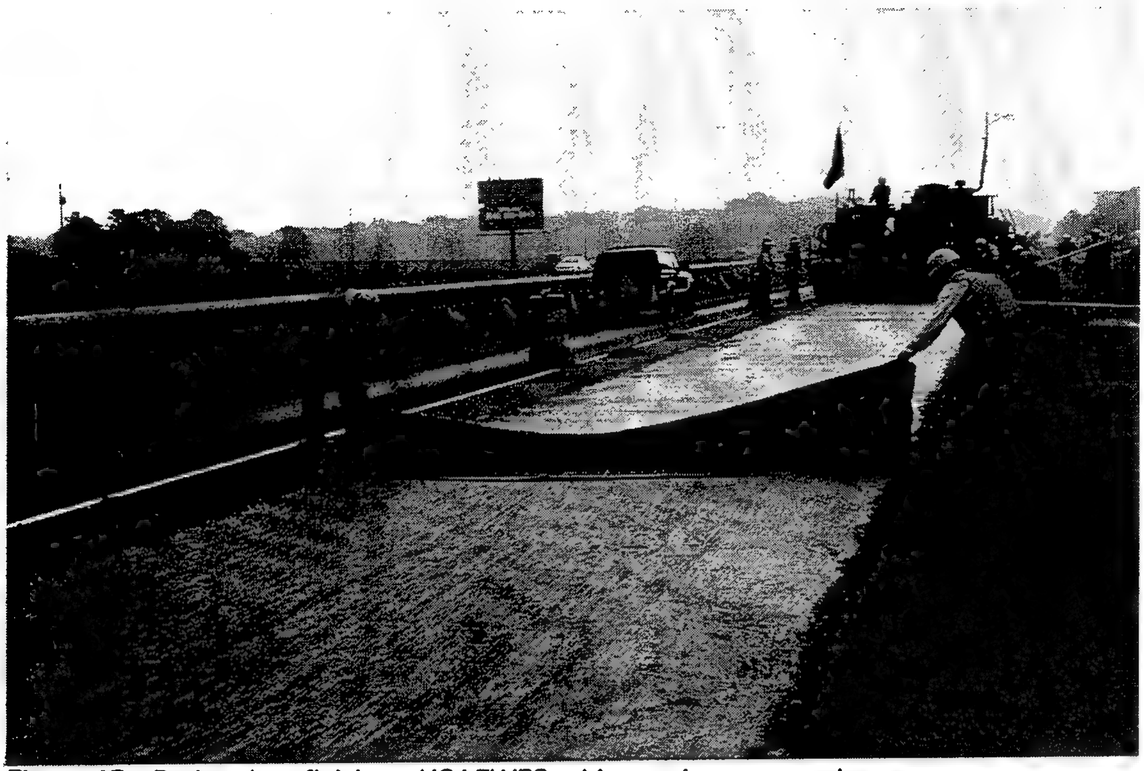

Figure 45. Burlap drag finish on USAEWES whitetopping test section

Figure 46. Application of curing compound on USAEWES whitetopping test section

intervals of approximately 57 m^3 (75 yd^3). Additional tests were performed at more frequent intervals to develop additional data. Acceptance testing was performed twice for each concrete producer. Unhardened concrete properties test results are shown in Table 18. Hardened properties measurements are given in Table 19.

The concrete met the compressive-strength requirement of 17 MPa (2,470 psi) at 30 hr. The entire whitetopping test section was opened to traffic at approximately 1700 hr on Thursday, 28 August 1997. Ages of the concrete at opening were approximately 52 hr for the MCIA section and 28 hr for the USAEWES section. At the time of opening to traffic, it is worth noting that while the USAEWES section met the specified strength requirements, the extra 24 hr of curing time allowed the concrete in the MCIA section to be considerably stronger.

Post construction evaluation

Ride quality and skid resistance. MDOT personnel evaluated the ride quality with an Ames Profilograph. Specifications permitted a maximum allowable profile index of 110 mm/km (7 in./mile). The average profile index for the entire project was 38 mm/km (2.4 in./mile). Only two small areas failed the bump/dip criterion and required grinding. One area was at the header between the MCIA section and the USAEWES section. The other was in the USAEWES section where a clump of HMA millings on the pavement shoulder was traversed by a track on the paver.

Skid testing was performed with MDOT's locked-wheel skid trailer (ASTM E 274 (ASTM 1995x)). The MCIA section had received additional texturing after hardening with a shotblasting machine. Only a small area of the USAEWES section received the shotblasted treatment because the Polyolefin fibers removed from the surface plugged the vacuum on the machine. It was determined the burlap-drag finish should provide adequate skid resistance on this section. Results from the skid-resistance evaluation indicated similar performance between each of the two test sections. The average skid number (SN) for the burlap drag finish on the USAEWES section was 51, while the average SN for the shotblasted surface on the MCIA section was 59.

FWD and HWD evaluation. After being in service for approximately 2 weeks, MDOT closed the lane to traffic on 19 September 1997 so an inspection could be performed. In addition to a visual inspection, evaluations were also performed with MDOT's FWD and USAEWES's HWD. HWD measurements were made along the center of the pavement section, between the wheel paths. The original intention was to take HWD readings approximately every 30 m (100 ft) along the pavement, as had been done in the preconstruction evaluation. However, due to the lack of a measuring wheel, locations for measurements were estimated by joint spacing and pacing.

Table 18
Whitetopping Quality-Control Results

Batch No.	Concrete Producer	Cumulative Volume, cu yd	Arrival Time	Initial Slump, mm	Water Added, L	Second Slump, mm	Unit Weight, kg/m	Relative Yield	Air Content, %	Concrete Temp, C	Air Temp, C	Water Added at Paver., L	Comments
1	A	6.1	605	5	45	40	2335	0.964	1.7	32.8	18.9	0	
2	A	12.2	610		45							0	
3	A	18.3	617	25	30		2299	0.981	1.8	29.4	18.9	0	
4	A	24.5	624		0							45	
5	A	30.6	627		0							45	
6	A	36.7	634		38							0	
7	A	42.8	634		0							0	
8	A	48.9	635		0							45	
9	A	55.0	646	45	30	45	2308	0.983	2.0	32.8	20.0	15	
	mid-portion sample		725	40	NA	NA	2305	0.985	2.7	33.9	20.0	NA	Specimens 239A
10	A	61.2	655									45	
11	A	67.3	700									45	
12	A	73.4	719									45	
13	B	79.5	730	40	0		2227	0.998	3.6	32.2	21.1	19	
14	B	85.6	803		30							0	
15	B	91.7	826	45	0		2239	0.994	3.6	31.7	23.3	0	
16	B	97.9	840		30							0	
17	B	104.0	844		23	75	2174	1.021	5.1	33.3	24.4	0	
18	B	110.1	848		23							0	
	mid-portion sample		900	70	NA	NA	2196	1.008	5.1	33.3	25.0	NA	Specimens 239B
19	B	116.2	853		30							0	
20	B	122.3	857		23							0	
21	B	128.4	904		0							0	
22	B	134.6	915		30							0	
23	B	140.7	924		0							0	
24	B	146.8	930		0							0	
25	A	152.9	930		30	75	2259	1.003	3.2	33.9	28.9	0	
26	A	159.0	945		0							0	
27	A	165.1	945		15							0	
28	A	171.3	955	50	0	NA	2281	0.991	3.0	33.9	30.0	0	
29	A	177.4	955		0							0	
30	A	183.5	1005		0							0	
	mid-portion sample		1016	80	NA	NA	2264	1.001	4.3	34.4	28.9	NA	Specimens 239A
31	A	189.6	1012		0							0	
32	A	195.7	1015		0							0	
33	A	201.8	1029		0							0	
34	A	208.0	1038		0							0	
35	A	214.1	1038		0							0	
36	A	220.2	1044		0							0	
37	B	226.3	1048	50	23		2175	1.015	5.4	35.0	32.8	0	
38	B	232.4	1058		0							0	
39	B	238.5	1110	55	0	NA	2206	1.000	4.8	34.4	32.8	0	
	mid-portion sample		1117	95	NA	NA	2191	1.007	5.3	35.0	32.8	NA	Specimens B
40	B	244.7	1112		0							0	
41	B	250.8	1119		0							0	
42	B	256.9	1125		0							0	
43	B	263.0	1144		0							0	
44	B	269.1	1155		0							0	

NA - not applicable or test not run.

Table 19
Whitetopping Hardened Properties Measurements, I-20 Whitetopping, 3M Fiber-Reinforced Concrete

Batch No.	Concrete Producer	Specimen ID	Specimen No.	Type Curing	Testing Lab	Test Date	Age, days	Compressive Str., MPa	E, Gpa	Flexural Str., MPa	Impact No. of Blows
9	A	A1	1	F	MDOT	27 Aug 97	29[1]	19.0			
			2	F	MDOT	27 Aug 97	29[1]	20.4			
			3	F	MDOT						
			4	F	MDOT						
			5	F	MDOT						
			6	F	MDOT						
			7	S	MDOT	10 Sep 97	14	34.7			
			8	S	MDOT	10 Sep 97	14	34.1			
			9	S	MDOT	24 Sep 97	28[1]	36.3			
			10	S	MDOT	24 Sep 97	28	37.0			
			11	S	WES	24-Sep-97	28	35.6	35.4		
			12	S	WES	24-Sep-97	28	37.3	34.9		
			13	S	WES	24-Sep-97	28	37.1	34.5		
			14	S	WES	24-Sep-97	28				57 / 118 / 220
			15	S	WES	24-Sep-97	28				175 / 156 / 190
			16	S	WES	24-Sep-97	28				100 / 190 / 66
			17	S	WES	24-Sep-97	28				183 / 159 / 148
			18	S	WES	24-Sep-97	28				118 / 265 / 181
			19	S	WES	30-Oct-97	72			4.95	
			20	S	WES	30-Oct-97	72			4.75	
			21	S	WES	30-Oct-97	72			4.25	
			22	S	WES						
18	B	B1	1	F	MDOT	27 Aug 97	28[1]	16.6			
			2	F	MDOT	27 Aug 97	28[1]	16.9			
			3	F	MDOT	27 Aug 97	31[1]	16.9			
			4	F	MDOT	27 Aug 97	31[1]	18.2			
			5	F	MDOT						
			6	F	MDOT						
			7	S	MDOT	10 Sep 97	14	30.2			
			8	S	MDOT	10 Sep 97	14	29.0			
			9	S	MDOT	24 Sep 97	28	36.7			
			10	S	MDOT	24 Sep 97	28	37.0			
			11	S	WES	24-Sep-97	28	23.6	30.1		
			12	S	WES	24-Sep-97	28	25.6	30.1		
			13	S	WES	24-Sep-97	28	35.0	30.4		
			14	S	WES	24-Sep-97	28				124 / 65 / 140
			15	S	WES	24-Sep-97	28				142 / 157 / 35
			16	S	WES	24-Sep-97	28				88 / 85 / 208
			17	S	WES	24-Sep-97	28				59 / 158 / 114
			18	S	WES	24-Sep-97	28				77 / 263 / 78
			19	S	WES						
			20	S	WES						
			21	S	WES						
			22	S	WES						

(Continued)

[1] Hours

Table 19 (Concluded)

Batch No.	Concrete Producer	Specimen ID	Specimen No.	Type Curing	Testing Lab	Test Date	Age, days	Compressive Str., MPa	E, Gpa	Flexural Str., MPa	Impact No. of Blows
3	A	A2	23	F	MDOT	27 Aug 97	27[1]	18.1			
			24	F	MDOT	27 Aug 97	27[1]	17.4			
			25	F	MDOT						
			26	F	MDOT						
			27	F	MDOT						
			28	F	MDOT						
			29	S	MDOT	10 Sep 97	14	30.6			
			30	S	MDOT	10 Sep 97	14	33.6			
			31	S	MDOT	24 Sep 97	28	35.6			
			32	S	MDOT	24 Sep 97	28	35.3			
			33	S	WES	24-Sep-97	28	34.4	35.3		
			34	S	WES	24-Sep-97	28	37.1	35.6		
			35	S	WES	24-Sep-97	28	34.6	34.8		
30	B	B2	23	F	MDOT	27 Aug 97	26[1]	15.2			
			24	F	MDOT	27 Aug 97	26[1]	16.1			
			25	F	MDOT	27 Aug 97	29[1]	16.5			
			26	F	MDOT	27 Aug 97	29[1]	16.0			
			27	F	MDOT	27 Aug 97	45[1]	19.0			
			28	F	MDOT	27 Aug 97	45	19.4			
			29	S	MDOT	10 Sep 97	14	26.1			
			30	S	MDOT	10 Sep 97	14	27.6			
			31	S	MDOT	24 Sep 97	28	30.8			
			32	S	MDOT	24 Sep 97	28	30.3			
			33	S	WES	24-Sep-97	28	33.3	N/A		
			34	S	WES	24-Sep-97	28	32.7	N/A		
			35	S	WES	24-Sep-97	28	N/A	N/A		

Adjustments were also required to prevent testing directly on joints. As a result, spacing for the measurements was uneven, resulting in a total of 37 test locations throughout the length of the 1,220-m (4,000-ft) section.

Numerous additional visual inspections were performed by MDOT and MCIA personnel without lane closures. Only low-severity spalling along some transverse control joint was noted during the first 3-1/2 months of service life. In late December 1997, a visual inspection indicated corner cracking in a few areas. The typical corner crack began at a transverse control joint approximately 1 m (3.3 ft) from the HMA median lane, and traversed diagonally towards the HMA median lane to a point approximately 1 m (3.3 ft) away from the control joint (Figure 47).

The lane was again closed to traffic on 25 January 1998 for a more detailed visual inspection and evaluations with the FWD and HWD. Visual inspection indicated a total of 19 corner cracks, 6 in the USAEWES section, and 13 in the

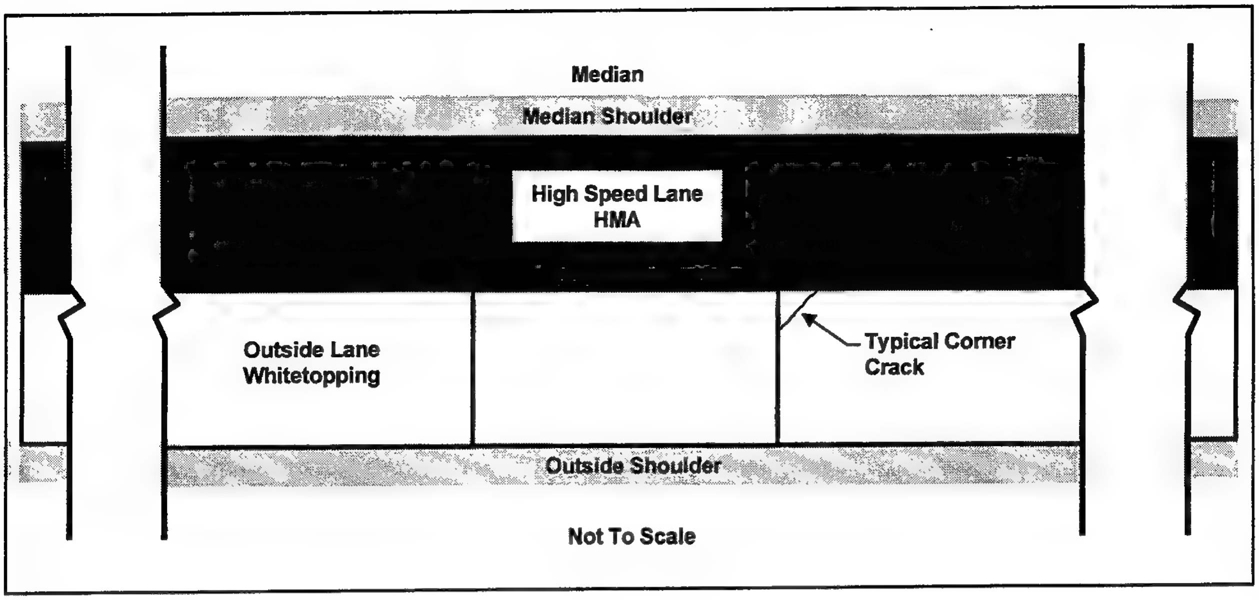

Figure 47. Typical corner crack

MCIA section. In the USAEWES section, 3 corner cracks were located in slabs having 7.6-m (25-ft) transverse control joint spacing, and 3 were located in slabs having 12.2-m (40-ft) joint spacing. No corner cracks were found in slabs having 4.6-m (15-ft) transverse nor in slabs having 1.8-m (6-ft) longitudinal and transverse control joint spacing. In the MCIA section, the 13 corner cracks were located in the 150-mm (5.9-in.-) thick whitetopping sections, both concrete without fibers and fibrillated polypropylene FRC sections. No corner cracks were found in slabs having a 200-mm (7.9-in.) thickness.

The results of the HWD evaluations indicated that, as expected, the ISM values had increased after the application of the TIW. Figure 37 shows the ISM values obtained during the two evaluations for each TIW design within the section. The ISM values were greater for the 200-mm (7.9-in.-) thick section and the polypropylene FRC 150-mm (5.9-in.-) thick section when compared to the PCC 150-mm- (6-in.-) thick section without fibers. Overall, the ISM values for the 100-mm- (3.9-in.-) thick Polyolefin FRC sections and the PCC 150-mm- (6-in.-) thick section without fibers were similar. All ISM values on the TIW were significantly higher than those obtained prior to these placement of the TIW, and illustrate the increased stiffness developed through the addition of the rigid TIW.

During the evaluation on 25 January 1998, MDOT evaluated the transverse control joints in the 150-mm (5.9-in.) TIW with their FWD. The results indicated that, although joints had been sawed every 1.82 m (6 ft), several of the neighboring joints had not cracked. This was evidenced by the very high

load transfer across the joints. Control joints were also evaluated in the USAEWES section. Indications were that all joints evaluated had cracked.

HWD results from each evaluation are given in Table 11. The average load applied for these HWD tests was over 84.5 kN (19,000 lbf), and the deflection at these loads varied with the pavement feature that was evaluated. The deflections were lower than those of the preconstruction evaluation, even though the applied load was greater. As might be expected, the lowest deflections were in the 200-mm (7.9-in.) concrete slabs without fibers. Interestingly, the 150-mm (5.9-in.) concrete slabs without fibers had values of deflection exceeding those of the 150-mm (5.9-in.) polypropylene FRC slabs and the 100-mm (3.9-in.) Polyolefin FRC slabs.

Summary

The postconstruction inspections and evaluations indicated that the TIW had performed very well during the first 5 months of service. The HWD and FWD evaluations verified the expected rise in pavement section stiffness with the TIW inlay. In addition to the increase in section stiffness, the TIW overlay provides a rut-resistant surface. The HWD and FWD evaluations also suggested that the addition of fibers, especially in large volumes, can decrease pavement section deflection under load. The validity of using this type of overlay for interstate applications will be its durability over a longer period of time. Additional discussion about the corner cracking, potential implication, and prevention can be found in Chapter 5.

5 Discussion

Fresh Properties

The Polyolefin fibers can be mixed and adequately distributed in a properly proportioned concrete mixture. Volumes up to 1.64 percent (14.9 kg/m^3) (25 lb/yd^3) were successfully mixed in this investigation. Larger quantities have been adequately mixed by others (Ramakrishnan 1993, 1995). There appear to be four keys to the adequacy of distribution. First is the bundling system unique to the Polyolefin fibers. The intact bundles (Figure 1) first distribute throughout the mixture. Then the water-soluble glue on the wrapping tape softens, the tape disperses, and the bundles open. Once the bundles begin to break open, fewer fibers are then concentrated in any single location. Therefore, there is a better opportunity for the fibers to disperse from the bundle without balling.

The second key is proper mixture proportioning. In general, compared to concrete mixture without fibers, any FRC mixture having fiber volumes very much in excess of about 0.2 percent will require some adjustments to the overall proportions. Adjustments are required to provide extra paste needed to coat the fibers and prevent harshness. Typical adjustments include increases in water content, fine-aggregate content, and water-reducing admixtures. The degree of adjustment depends upon the type and volume of fibers being used, the type of coarse and fine aggregates, and w/(c+m) of the FRC.

The third key is shearing action of the mixer. While FRC can be mixed in most concrete mixers, the mixing time necessary to properly distribute the fibers will vary depending upon the fiber loading and the shearing action of the mixer. Mixers that generate more shearing action generally uniformly distribute the fibers uniformly with less mixing time than will be required for mixers with less shearing action.

The fourth key is the slump of the concrete (especially prior to the introduction of the fibers). Higher slump (175- to 225-mm) (7- to 9-in.) mixtures can sometimes substantially float the fiber bundles on the top surface of the concrete in the mixer, preventing them from being thoroughly folded into the mixture. This effectively reduces the shearing effects of the mixing

action upon the bundles themselves. Low-slump (25- to 50-mm) (1- to 2-in.) mixtures sometimes have less free water available to soften the glue on the wrapping tape, slowing the dissolution of the glue. In either case, more mixing time can be required to open the bundles.

With the many variables involved in the production of concrete mixtures, it is not feasible to provide exact guidelines for proportioning. In general, mixtures can be proportioned according to the procedures described in ACI 211.1 (ACI 1997). However, based upon the data obtained from the laboratory investigation and the whitetopping demonstration project, some additional general guidelines on proportioning and mixing appear appropriate and are summarized as follows:

a. With the inclusion of 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of either Polyolefin fiber, an increase of approximately 15 to 25 percent in the water content above that required for concrete without fibers can be expected. With the inclusion of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) of either Polyolefin fiber, an increase of approximately 10 to 20 percent in the water content above that required for concrete without fibers can be expected. The larger increases in the water content will generally be required in mixtures having higher w/(c+m). Mixtures having lower w/(c+m) have higher paste contents, and as a result may already have a higher water content. The extra paste provides needed coating for the fibers, lessening the harshness brought on by the addition of the fibers. However, as has been previously mentioned, better proportions can often be achieved by a balanced increase in mortar content (as influenced by the S/A) and paste content (as influenced by the water content) rather than by an increase in the paste content alone. The effective increase in water content can be achieved with water-reducing admixtures if desired.

b. The fine-aggregate content generally should be increased when fiber loadings of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) or higher of either Polyolefin fiber are used. Although the increase in fine aggregate is not absolutely necessary, it prevents the mixtures from becoming harsh. A nominal increase in the fine-aggregate content generally results in the mixtures becoming more workable. The amount of the increase will depend upon several factors, among which are the type (crushed or natural) of the coarse aggregate and the paste content of the mixture. In general, it appears that increases in the S/A of 2 to 5 percent by volume are appropriate with fiber loadings of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) of either Polyolefin fiber. Increases in the S/A of 5 to 10 percent by volume appear appropriate with fiber loadings of 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of either Polyolefin fiber. The larger increases will generally be required with crushed coarse aggregates and higher w/(c+m). Mixtures having all natural aggregates and lower w/(c+m) will usually respond positively to smaller increases.

c. The optimum slump for efficient opening of the fiber bundles appears to be from 100 to 150 mm (4 to 6 in.). Mixers producing more shearing action will be more efficient in opening the bundles of fibers.

d. When fiber loadings of 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of either Polyolefin fiber are used, a slump decrease of 50 to 100 mm (2 to 4 in.) can be expected in a mixture immediately as the fibers fully distribute. When fiber loadings of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) of either Polyolefin fiber are used, a slump decrease of 25 to 75 mm (1 to 3 in.) can be expected in a mixture immediately as the fibers fully distribute.

e. When FRC with Polyolefin fibers is being mixed in a truck mixer, it is necessary to ensure that the concrete without fibers has been uniformly mixed prior to the addition of the fibers. Premature addition of the fibers can prevent the proper generation of entrained air in the mixture and also interfere with the uniform distribution of the fibers. The appropriate amount of mixing time both before and after the addition of the fibers must be determined for each placement. Generally, the concrete without fibers should be mixed according to ASTM C 94 (ASTM 1995) prior to the addition of the fibers. After the fibers have been added, mixing should be continued until a visual examination of the FRC inside the truck mixer shows no evidence of unbroken bundles. A mixing time of 5 to 10 min after addition of the fibers appears to be typical of that required. As an example, the required mixing time after addition of the fibers on the whitetopping demonstration project was 8 to 10 min. These were high-slump mixtures (200 to 250 mm) (8 to 10 in.) prior to the addition of the fibers. As discussed, the initially high slump contributed to the necessity of longer mixing times.

f. When FRC with Polyolefin fibers is being mixed in a central mixing plant, the fibers can be added to the mixer before any of the other materials (Ramakrishnan 1993). Mixers in central mixing plants typically generate better shearing action than do truck mixers, and thus are both more efficient at mixing the concrete and distributing the fibers. For example, to achieve uniform mixing, a typical central mixer may require only 60 to 120 sec of mixing time after all of the materials have been charged into the drum, whereas a typical truck mixer may require up to 6 min of mixing time to achieve uniform mixing. Due to the efficiency of the mixing action in a typical central mixer, early opening of the fiber bundles does not interfere with uniformity. In fact, Ramakrishnan (1993) determined the shortest mixing time required to achieve uniform mixing of Polyolefin FRC in a central mixer was when the fibers were added to the mixer drum prior to any of the other materials. However, as was the case with producer B in the whitetopping project, if the fibers are added to the concrete after it has been discharged from the central mixer into the truck mixer

for transportation, the mixing should be continued in the truck mixer until a visual examination of the FRC inside the mixer shows no evidence of unbroken bundles. A mixing time of 5 to 10 min after addition of the fibers again appears to be typical of that required.

Hardened Properties

The data indicated that hardened properties of FRC mixtures dependent upon the post-crack performance were enhanced by inclusion of the Polyolefin fibers. Variables influencing particular areas of performance were consistent throughout the investigation. One unexpected result was that neither S/A nor mortar content appeared to be a significant factor in flexural strength, flexural toughness, or impact resistance. It had been anticipated that increases in the S/A (mortar content) would result in a decrease in the flexural and impact properties. However, analysis of the data did not support this hypotheses. The data indicate that the S/A can be increased as necessary to prevent harshness in the unhardened mixtures without being detrimental to hardened flexural and impact properties.

Some unexpected contrasts did surface between the different phases of the investigation. While it is not possible to determine with certainty the reason for these differences, some possibilities are discussed below.

Impact resistance

As stated in Chapter 3, the data indicated a statistical difference between the impact results from Phase I and Phase II. The data indicated that fiber loading was a significant factor contributing to the impact resistance of both Phases I and II data. Except for the portland cement, all materials used to proportion the concrete mixtures in Phases I and II were the same. There are no data to suggest a significant difference in the strength production of the two lots of portland cement. Implications are that the contrast in impact values most likely result from differences in the bonding of the Polyolefin fibers to the cementitious matrix.

Prior to their introduction into a concrete mixture, the Polyolefin fibers have a very smooth surface not conducive to bonding. However, during mixing, contact with the aggregate particles abrades and roughens the surface of the fibers (Ramakrishnan 1993). This roughening facilitates good bonding of the fiber to the cementitious matrix. The roughening appears to occur exponentially with mixing time. Although not proven by Ramakrishnan (1993), it is reasonable to expect that the exponential rate of roughening is influenced by the shearing action generated by the mixer and the batch size in the mixer. This reasoning provides a possible explanation for the difference in the impact results from Phases I and II. Batch sizes for the mixtures produced

in Phase II were larger than those produced in Phase I. In some cases, because of the larger batch sizes, different concrete mixers were used. It is possible that these differences in batch sizes, and in some cases concrete mixers, could have resulted in different degrees of roughening of the fibers.

While this suggestion that the roughening of the fibers is quite sensitive to the mixing time may cause concern, further consideration suggests that it is not likely to be a problem in actual production of the FRC for a construction project. Recall that these laboratory batches were mixed according to the time requirement given in ASTM C 192 (ASTM 1995m). That means that the total mixing time for the concrete was 5 min (3 min mixing, 3 min resting, and 2 min mixing). The Polyolefin fibers were added after 1 or 2 min of the initial 3-min mixing period. That means that the fibers were only mixed for either 3 or 4 min. While this was obviously enough time to adequately distribute the fibers in the laboratory batches, it could have been borderline in sufficiently roughening the fibers. Batch size and type of mixer could have had enough influence upon the shearing action to result in different levels of roughening. In an actual construction project, mixing times are likely to be much longer than those used in the laboratory, in which case thorough roughening of the fibers should easily be accomplished.

Toughness

Overall, the toughness values for the Polyolefin FRC from Phase I were less than those previously reported and those measured from Phase II of this investigation. Ramakrishnan (1997) reported that 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers provided toughness values similar to 39.2 kg/m^3 (66 lb/yd^3) (0.50-percent volume) of a popular hooked-end steel fiber. However, the toughness results from the Phase I investigation presented above indicate a favorable comparison between 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) of the Polyolefin fibers and 19.6 kg/m^3 (33 lb/yd^3) (0.25-percent volume) of a popular hooked-end steel fiber. The larger quantity of the steel fiber provided higher toughness values than the Polyolefin fibers. Interestingly, the toughness values from Phase II of this investigation were comparable to those reported by Ramakrishnan (1995). As described previously for the impact results, one possible explanation for the discrepancy is variation in the bonding of the Polyolefin fibers to the cementitious matrix. Better shearing action during mixing could have resulted in more effective abrading of the surface of the fibers, hence better bond. Better bond could have produced the improved toughness performance in the Phase II FRC.

Whitetopping Demonstration Project

Overall, the whitetopping project is judged to have been very successful. To the credit of all parties involved in the project, the planning and execution proceeded at a very rapid pace. Each challenge, whether engineering, planning, or financial, was quickly and successfully overcome. The project was taken from conception through construction in approximately 6 months. Postconstruction evaluations up until the time of the writing of this report have been documented. MDOT will continue to monitor and evaluate the performance of the TIW indefinitely. MDOT has indicated informally that the performance to date is satisfactory enough that plans are already being made to place more TIW, possibly in 1999. At this time, the decision has not been made as to which of the variations of TIW will be selected for use. Other variations of TIW could also be considered.

There were two somewhat negative issues arising from the TIW project that warrant additional discussion and possible explanation. One was the issue of an excessive amount of extra Polyolefin FRC being required for the USAEWES section. The second was the issue of corner cracking. These two issues are discussed below.

Yield

As stated in Chapter 4, a total of approximately 260 m^3 (340 yd^3) of Polyolefin FRC was placed in the USAEWES section. Initial estimates were for approximately 226 m^3 (296 yd^3). The difference of 34 m^3 (44 yd^3) was an increase of approximately 15 percent. This overage is larger than is commonly expected. The overage on the MCIA section placed the previous day was approximately 3 percent. Considerable discussion among staff members of the MDOT, MCIA, USAEWES, 3M, and concrete producers has not resulted in a satisfactory explanation for this discrepancy.

One suggestion has been that the apparent shortage must somehow be related to the Polyolefin fibers. However, there are no solid data to support this claim. Yield determinations from the quality-control measurements indicate that the deliveries to the placement site were generally within 1 percent of the theoretical. Another exercise involving summing of the masses of all material batched throughout the placement and calculating the overall yield suggests that, overall, there was a small overage in yield. Unit weight measurements were made by ACI Grade I Certified Field Technicians with additional oversight by qualified engineers. The body of data simply does not support the suggestion that the Polyolefin FRC consistently underyielded. In addition, there has been no evidence of significant underyield associated with the Polyolefin FRC on any of the other documented projects where large quantities of the Polyolefin FRC was used (Ramakrishnan 1995;

Ramakrishnan, Strand, and MacDonald 1996; Ramakrishnan and MacDonald 1997; Jagodzinski 1998).

Another suggestion has been that the apparent shortage could be related to an excessive amount of the Polyolefin FRC failing to discharge from the truck mixers. This suggestion has some merit since the TIW mixtures were quite sticky due to the large quantity of cementitious materials. Also the abundance of fibers could cause extra buildup around the fins inside the mixer. However, upon observation of the mixer washout area, there did not appear to be an excessive amount of material washed out of the mixer. An amount as large as 34 m^3 (44 yd^3) would seem to be quite noticeable. It appeared that the amount of concrete lost inside the mixer drum was similar to that of concrete without fibers. It is estimated that the amount of concrete lost inside the mixer was approximately 1 to 3 percent. Therefore, this suggestion does not appear to provide an adequate answer to the shortage.

Another suggestion has been that perhaps the placement area was larger than anticipated due to variations in the depth of the milling. MDOT personnel have indicated that the milling depth was relatively consistent at 100 mm (3.9 in.), and that the variations found in the sections milled to a depth of 100 mm (3.9 in.) should not be any greater than the variations found in the deeper milled sections. However, it can be shown that equal variation in milling depth will have a larger impact upon the overall volume of the thinner sections, when volume variations are expressed as a percentage. For example, consider a pavement section 614 m (2,014 ft) long and 3.66 m (12 ft) wide. In the first scenario, suppose the specified milling and placement depth was to be 150 mm (5.9 in.) but the average milling depth (TIW placement depth) was actually 163 mm (6.4 in.), an increase of 13 mm (0.5 in.). The volume of the design area would be 337 m^3 (441 yd^3). The volume required to fill the additional area would be 29 m^3 (38 yd^3). In the second scenario, suppose the specified milling and placement depth was to be 100 mm (3.9 in.) but the average milling depth (TIW placement depth) was actually 113 mm (4.4 in.), the same increase of 13 mm (0.5 in.). The volume of the design area would be 225 m^3 (295 yd^3). The volume required to fill the additional area would again be 29 m^3 (38 yd^3). Yet as a percentage of the total volume, the additional volume is approximately 8.5 percent of the 150-mm- (5.9-in.-) deep section, while it is approximately 13 percent of the 100-mm (3.9-in.-) deep section. Several depth measurements were made on the milled area of the USAEWES section prior to placement of the FRC. Each measurement indicated minimal deviation from the specified 100-mm (3.9-in.) depth. However, no cores have been taken from the pavement to verify the actual average depth of the TIW.

In reality, the actual cause of the yield discrepancy most likely is the result of a combination of several factors, some of which may not have been considered above. However, given the available data, it is the opinion of the authors that a plausible explanation for the apparent shortage of concrete was variation in the depth of the TIW. There is no evidence to support an under-yielding problem in the concrete. Neither was there sufficient physical

evidence to support the suggestion that an excessive amount of material failed to discharge from the trucks. Given the lack of evidence to support these two theories, it appears reasonable that on average, the USAEWES TTW was somewhat thicker than originally planned. However, this cannot be confirmed nor disproven until cores have been taken for length measurements.

Corner cracking

After approximately 3-1/2 months of service life, corner cracks as described in Chapter 4 were found in 6 slabs in the USAEWES section. Corner cracks were found in 13 slabs in the MCIA section. FWD evaluation of the corner cracks and adjacent transverse control joints in the MCIA section indicated that some of the control joints had not cracked. Implications are that had all of the transverse control joints cracked properly, curling and other traffic-related stresses may not have been sufficient to cause the corner cracking. The lack of corner cracking in neighboring areas where all sawed control joints cracked properly supports this conclusion. The solution to prevention of corner cracking in these TTW sections could be to ensure sawed control joints are cut in a timely manner and to a proper depth to ensure proper cracking.

FWD and HWD evaluations suggested that all sawed control joints did properly crack within the USAEWES section. Initial examination indicates that the corner cracks are caused by curling and traffic-related stresses. Based on existing data from this investigation, a possible solution to prevent corner cracks from forming would appear to be limiting transverse joint spacing to a maximum of 4.6 m (15 ft). All six corner cracks found on the USAEWES section at the time of writing of this report have been on slabs having 7.6-m (25-ft) and 12.2-m (40 ft) transverse joint spacing. No corner cracks have yet been found on slabs having 4.6-m (15-ft) transverse, nor 1.8-m (6 ft) transverse and longitudinal joint spacing.

One additional factor relating to the unwanted cracking should be considered. Even though some corner cracks have formed, it is unknown at this time how long the TTW will remain in service before the cracked sections will require maintenance or replacement. It is reasonable to assume that the sections having unwanted random cracks of any kind will likely require maintenance or replacement sooner than if the unwanted cracks were not present. However, one of the proven benefits of FRC, such as that having 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume), is that considerable load can be transferred across the crack by the fibers. Indications are that at this time the cracks are being held tightly together by the fibers. As long as the cracks are being held tightly together by the fibers, it is possible that the TTW could have a long service life, even with the unwanted cracks being present. The actual ramifications of the unwanted corner cracks now present, and others that could later form, can only be determined by monitoring and evaluating the performance of the pavement over its entire service life, however long that may be.

6 Conclusions and Recommendations

Conclusions

Performance

Based on the results of the laboratory and field evaluations of the 3M Polyolefin fibers, the following conclusions appear warranted:

a. Each of the two types of Polyolefin fibers can be uniformly mixed in quantities up to 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) in properly proportioned concrete mixtures. The 3M fiber delivery system is key to the adequate distribution of the large volume of fibers. The fiber bundles, encased with tape and water-soluble glue, initially disperse intact throughout the mixture. After a few minutes of mixing, the glue dissolves, the tape disperses, and the fibers distribute in a somewhat timed-release manner. Since the bundles have already been distributed throughout the mixture, there are fewer fibers to distribute at any incremental location once the bundles begin to break open. This system facilitates the uniform distribution of large volumes of the Polyolefin fibers.

b. Inclusion of the Polyolefin fibers in quantities of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) and above provides considerable additional material surface area in the mixture. This additional surface area must be coated by paste. Adjustments to the overall mixture proportions will be required to provide the extra paste. Balanced increases to both the paste content and mortar content generally are most effective in maintaining slump while preventing harshness. Effective use of water-reducing admixtures can minimize the necessary increase in paste content.

c. Addition of each type of Polyolefin fiber in quantities of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) to 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) results in significant improvements in post-crack

hardened properties. Hardened properties most improved are flexural toughness and impact resistance. Polyolefin FRC having fiber quantities of 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) has flexural toughness and impact resistance similar to that of FRC with 19.6 kg/m^3 (33 lb/yd^3) (0.25-percent volume) to 39.2 kg/m^3 (66 lb/yd^3) (0.50-percent volume) of a popular hooked-end steel fiber.

d. As a general rule, the larger Type 50/63 improves impact resistance more than the smaller Type 25/38 fibers at quantities of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume) and above. Smaller quantities of either of the two fibers provide similar impact resistance.

e. Flexural toughness of FRC with each of the two types of Polyolefin fibers is similar at all fiber loadings evaluated. However, indications are that, at fiber loadings higher than those evaluated in this investigation, the larger type 50/63 fibers would begin to provide better flexural toughness.

f. Other hardened properties measured in this investigation (compressive strength, flexural strength, elastic modulus, freezing-and-thawing resistance, chloride permeability, and drying shrinkage) appeared to be unaffected by inclusion of the Polyolefin fibers in quantities up to 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume).

g. FRC with 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) Polyolefin fibers can be mixed in a truck mixer and placed with a slipform paver. Attention to batching sequences and mixing times will ensure mixture uniformity.

h. FRC with 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) Polyolefin fibers appears to be a viable option for UTW or TIW. The last comprehensive evaluation of the TIW test section on I-20 was after a service life of approximately 5 months. Performance over this period of time was good. Six unwanted corner cracks did form in the test section, possibly due to curling. At the time of writing of this report, the cracks were being held tightly together by the fibers. The true performance of the TIW can only be determined by monitoring and evaluating its performance over a longer period of time.

Commercialization

3M has aggressively marketed the Polyolefin fibers through personal contacts, providing technical assistance to users and potential users, providing technical literature describing the fibers, and pursuing research through the academia. Numerous reports and papers have been published as a result of research 3M has either funded or participated in. The latest revision of ACI 544.1R (ACI 1998) includes information describing the Polyolefin fibers

and performance characteristics of FRC with the fibers. Several notable projects have been completed using the Polyolefin fibers.

However, the 3M Company has made a decision to discontinue marketing the Polyolefin fibers. This decision was unexpected, especially in light of the good performance of the fibers. 3M is seeking to negotiate an agreement with another company who would purchase the rights to the fiber and then continue to market the fiber. At the time of writing of this report, such an agreement has not been reached. 3M has indicated that fibers will be available for an indefinite period of time for customers who wish to make purchases. However, marketing and technical support will not be available from 3M after 30 June 1998.

Recommendations

In light of the good performance of the Polyolefin fibers and the aggressive, and successful, commercialization effort to market the fibers, it is recommended that 3M persist in its efforts to find a suitable partner to continue to market the Polyolefin fibers. Considerable effort and resources, both by 3M and the U.S. Army Corps of Engineers, have been invested in the research, development, and commercialization of the Polyolefin fibers. These efforts have resulted in a good product and a potentially growing market.

It is recommended that monitoring and evaluation of the TIW test section on I-20 be continued indefinitely. Attempts should be made to correlate the performance of the TIW with the hardened properties of the FRC. The ultimate goal should be to develop design tools which will consider the thickness and quality of the existing HMA pavement section, as well as the hardened properties of the FRC when designing the thickness and control joint spacing criteria for a whitetopping application.

For future TIW applications using the Polyolefin fibers (assuming the TIW would be placed on a structurally sound HMA pavement and that the existing TIW continues to perform adequately), two designs different from those used on the USAEWES test section on I-20 are recommended for consideration:

a. First, a section having a thickness of 100 mm (3.9 in.), Polyolefin fiber loading of 8.9 kg/m^3 (15 lb/yd^3) (0.98-percent volume), and a transverse joint spacing of 4.6 m (15 ft). No unwanted cracks have yet been found on the USAEWES test section having control joint spacing of 4.6 m (15 ft). Obviously, some flexural toughness and impact resistance will be lost by reducing the fiber loading from 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume) to 8.9 kg/m^3 (15 lb/yd^3) (0.98 percent volume). However, at this time, it is unknown how much flexural toughness and impact resistance are needed for adequate performance in an application of this type. In addition, the reduction in the fiber loading will reduce the cost of the FRC.

b. Second, a section having a thickness of 100 mm (3.9 in.), Polyolefin fiber loading of 14.9 kg/m^3 (25 lb/yd^3) (1.64-percent volume), and no sawed transverse nor longitudinal control joints. It should be anticipated that random transverse shrinkage cracks would eventually form at some spacing along long sections of this type. However, indications are (Ramakrishnan 1996) that the high concentration of fibers would hold the crack tightly together such that working and raveling would not be a problem. The theory behind this suggestion is that a joint, sawed 25 mm (1 in.) deep in a whitetopping section 100 mm (3.9 in.) deep, reduces the number of fibers bridging the crack by 25 percent. A crack allowed to form naturally will have the full measure of fibers available to transfer load across the crack.

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Appendix B
Test Results

Table B1
Chemical and Physical Properties of Portland Cement

Property, % by Mass	Lot #1 (950591)	Lot #2 (960294)
SiO_2	21.3	21.3
Al_2O_3	4.6	4.0
Fe_2O_3	3.2	3.2
CaO	62.2	61.7
MgO	3.5	3.9
SO_3	2.9	3.0
Loss on Ignition	1.7	1.2
Insoluble Residue	0.14	0.10
Na_2O	0.03	0.11
K_2O	0.39	0.63
	0.29	0.52
TiO_2	0.26	0.24
P_2O_5	-	0.10
C_3A	8	6
C_2S	47	47
C_2S	25	25
C_4AF Alkalies-total as Na_2O	10	10
Physical Test	**Lot # (950591)**	**Lot # (960294)**
Surface area, m^2/kg (air permeability)	353	379
Autoclave expansion, %	0.01	0.05
Initial set, min (Gillmore)	190	210
Final set, min (Gillmore)	265	300
Air content, %	7	7
Compressive strength, 3-day, psi	3,450	3,180
Compressive strength, 7-day, psi	4,090	4,020

Table B2
Chemical and Physical Properties of Fly Ash

SiO_2, %	37.4
Al_2O_3, %	19.8
Fe_2O_3, %	8.2
Sum, %	65.4
MgO, %	4.3
SO_3, %	2.3
Moisture content, %	0.1
Loss on ignition, %	0.3
Available alkalies (28 day), %	1.84
Fineness (45 μm), % retained	15
Fineness variation, %	2
Water requirement, %	94
Density, Mg/m^3	2.59
Density variation, %	0.03
Strength activity index w/cement, 7 day, %[1]	92
Strength activity index w/cement, 28 day, %[1]	103

[1] Cement used: Canakale Cement, Istanbul, Turkey (WES-76-95).

Table B3
Aggregate Properties

	Percent Passing	
Sieve Size	Aggregate	Fine Aggregate
25.0 mm	100	
19.0 mm	98	
12.5 mm	64	
9.5 mm	34	
4.75 mm	3	98
2.36 mm		82
1.18 mm		71
600 μm		62
300 μm		27
150 μm		3
Specific gravity	2.73	2.58
Absorption, %	0.4	1.7

Table B4
Mixture Proportions Summary, Phase I

Mixture ID	w/(c+m)	S/A	Vol. Air (Design) m^3	Vol. Water m^3	Vol. Cement m^3	Vol. Fly Ash m^3	Vol. Fine Aggregate m^3	Vol. Coarse m^3	Vol. Fiber m^3	Type Fiber	Vol. Paste m^3	Vol. Mortar m^3	Paste/ Mortar
AL-0	0.4	40	0.06	0.143	0.0908	0.0227	0.2734	0.4101	0	N/A	0.3165	0.5899	0.536532
P2AL-1.5	0.4	40	0.06	0.145	0.0921	0.023	0.2716	0.4073	0.001	Type 50/63	0.3201	0.5917	0.540984
P2AL-6.25	0.4	40	0.06	0.15	0.0952	0.0238	0.2668	0.4001	0.0041	Type 50/63	0.329	0.5958	0.552199
P2AL-15	0.4	40	0.06	0.155	0.0984	0.0246	0.2609	0.3913	0.0098	Type 50/63	0.338	0.5989	0.564368
P2AL-20	0.4	40	0.06	0.162	0.1029	0.0257	0.2545	0.3818	0.0132	Type 50/63	0.3506	0.6051	0.579408
P2AM-6.25	0.4	40	0.06	0.146	0.0927	0.0232	0.3033	0.3707	0.0041	Type 50/63	0.3219	0.6252	0.514875
P2AM-15	0.4	40	0.06	0.157	0.0997	0.0249	0.2919	0.3567	0.0098	Type 50/63	0.3416	0.6335	0.539227
P2AM-20	0.4	40	0.06	0.168	0.1066	0.0267	0.2818	0.3445	0.0132	Type 50/63	0.3613	0.6431	0.56181
P2AM-25	0.4	40	0.06	0.17	0.1079	0.027	0.2785	0.3403	0.0164	Type 50/63	0.3649	0.6434	0.567143
P2AH-15	0.4	40	0.06	0.167	0.106	0.0265	0.3154	0.3153	0.0098	Type 50/63	0.3595	0.6749	0.532672
P2AH-20	0.4	40	0.06	0.167	0.106	0.0265	0.3137	0.3138	0.0132	Type 50/63	0.3595	0.6732	0.534017
P2AH-25	0.4	40	0.06	0.17	0.1079	0.027	0.3094	0.3094	0.0164	Type 50/63	0.3649	0.6743	0.541154
BL-0	0.48	40	0.06	0.148	0.0783	0.0196	0.2776	0.4165	0	N/A	0.3059	0.5835	0.52425
P2BL-1.5	0.48	40	0.06	0.148	0.0783	0.0196	0.2772	0.4159	0.001	Type 50/63	0.3059	0.5831	0.52461
P2BL-6.25	0.48	40	0.06	0.153	0.081	0.0202	0.2727	0.409	0.0041	Type 50/63	0.3142	0.5869	0.535355
P2BL-15	0.48	40	0.06	0.178	0.0942	0.0235	0.2538	0.3807	0.0098	Type 50/63	0.3557	0.6095	0.583593
P2BL-20	0.48	40	0.06	0.185	0.0979	0.0245	0.2478	0.3718	0.0132	Type 50/63	0.3674	0.6152	0.597204
P2BM-6.25	0.48	45	0.06	0.161	0.0852	0.0213	0.3008	0.3676	0.0041	Type 50/63	0.3275	0.6283	0.521248
P2BM-15	0.48	45	0.06	0.175	0.093	0.023	0.288	0.351	0.01	Type 50/63	0.351	0.639	0.549296
P2BM-20	0.48	45	0.06	0.18	0.0952	0.0238	0.2826	0.3454	0.0132	Type 50/63	0.359	0.6416	0.559539
P2BM-25	0.48	45	0.06	0.183	0.0968	0.0242	0.2789	0.3408	0.0164	Type 50/63	0.364	0.6429	0.566184
P2BH-15	0.48	50	0.06	0.173	0.0915	0.0229	0.3214	0.3214	0.0098	Type 50/63	0.3474	0.6688	0.519438
P2BH-20	0.48	50	0.06	0.175	0.0926	0.0231	0.3181	0.3182	0.0132	Type 50/63	0.3507	0.6688	0.524372
P2BH-25	0.48	50	0.06	0.178	0.0942	0.0235	0.314	0.314	0.0164	Type 50/63	0.3557	0.6697	0.531133
P1AL-1.5	0.4	40	0.06	0.148	0.094	0.0235	0.2694	0.4041	0.001	Type 25/38	0.3255	0.5949	0.547151
P1AL-6.25	0.4	40	0.06	0.155	0.0984	0.0246	0.2632	0.3947	0.0041	Type 25/38	0.338	0.6012	0.562209
P1AL-15	0.4	40	0.06	0.16	0.1016	0.0254	0.2573	0.3859	0.0098	Type 25/38	0.347	0.6043	0.574218

(Sheet 1 of 3)

Table B4 (Continued)

Mixture ID	w/(c+m)	S/A	Vol. Air (Design) m^3	Vol. Water m^3	Vol. Cement m^3	Vol. Fly Ash m^3	Vol. Fine Aggregate m^3	Vol. Coarse m^3	Vol. Fiber m^3	Type Fiber	Vol. Paste m^3	Vol. Mortar m^3	Paste/ Mortar
P1AL-20	0.4	40	0.06	0.166	0.1054	0.0263	0.2517	0.3775	0.0132	Type 25/38	0.3577	0.6094	0.586971
P1AL-25	0.4	40	0.06	0.169	0.1073	0.0268	0.2482	0.3724	0.0164	Type 25/38	0.3631	0.6113	0.59398
P1AM-6.25	0.4	45	0.06	0.148	0.094	0.0235	0.3017	0.3687	0.0041	Type 25/38	0.3255	0.6272	0.518973
P1AM-15	0.4	45	0.06	0.156	0.099	0.0248	0.2927	0.3577	0.0098	Type 25/38	0.3398	0.6325	0.537233
P1AM-20	0.4	45	0.06	0.17	0.1079	0.027	0.2799	0.3421	0.0132	Type 25/38	0.3649	0.6448	0.565912
P1AM-25	0.4	45	0.06	0.172	0.1092	0.0273	0.2768	0.3384	0.0164	Type 25/38	0.3685	0.6453	0.571052
P1AH-20	0.4	50	0.06	0.169	0.1073	0.0268	0.3119	0.3119	0.0132	Type 25/38	0.3631	0.675	0.537926
P1AH-25	0.4	50	0.06	0.17	0.1079	0.027	0.3094	0.3094	0.0164	Type 25/38	0.3649	0.6743	0.541154
P1BL-1.5	0.48	40	0.06	0.151	0.0799	0.02	0.2752	0.4129	0.001	Type 25/38	0.3109	0.5861	0.530456
P1BL-6.25	0.48	40	0.06	0.153	0.081	0.0202	0.2727	0.409	0.0041	Type 25/38	0.3142	0.5869	0.535355
P1BL-15	0.48	40	0.06	0.173	0.0915	0.0229	0.2571	0.3857	0.0098	Type 25/38	0.3474	0.6045	0.57469
P1BL-20	0.48	40	0.06	0.18	0.0952	0.0238	0.2512	0.3767	0.0132	Type 25/38	0.359	0.6102	0.588332
P1BL-25	0.48	40	0.06	0.187	0.099	0.0247	0.2452	0.3678	0.0164	Type 25/38	0.3707	0.6159	0.601883
P1BM-6.25	0.48	45	0.06	0.161	0.0852	0.0213	0.3008	0.3676	0.0041	Type 25/38	0.3275	0.6283	0.521248
P1BM-15	0.48	45	0.06	0.173	0.0915	0.0229	0.2893	0.3535	0.0098	Type 25/38	0.3474	0.6367	0.545626
P1BM-20	0.48	45	0.06	0.18	0.0952	0.0238	0.2826	0.3453	0.0132	Type 25/38	0.359	0.6416	0.559539
P1BM-25	0.48	45	0.06	0.182	0.0963	0.0241	0.2796	0.3417	0.0164	Type 25/38	0.3624	0.642	0.564486
P1BH-20	0.48	50	0.06	0.178	0.0942	0.0235	0.3156	0.3156	0.0132	Type 25/38	0.3557	0.6713	0.529867
P1BH-25	0.48	50	0.06	0.18	0.096	0.0238	0.312	0.3119	0.0164	Type 25/38	0.3598	0.6718	0.535576
DAL-33	0.4	40	0.06	0.151	0.09587	0.02397	0.26667	0.4	0.0025	Steel	0.33084	0.59751	0.553698
DAL-66	0.4	40	0.06	0.157	0.09968	0.02492	0.26136	0.39204	0.005	Steel	0.3416	0.60296	0.566538
DAL-85	0.4	40	0.06	0.16	0.10159	0.0254	0.25865	0.38797	0.0064	Steel	0.34699	0.60564	0.572931
DAM-33	0.4	45	0.06	0.151	0.09587	0.02397	0.3008	0.36666	0.0025	Steel	0.33084	0.63164	0.523779
DAM-66	0.4	45	0.06	0.151	0.09587	0.02397	0.29887	0.36529	0.005	Steel	0.33084	0.62971	0.525385
DAM-85	0.4	45	0.06	0.15	0.09524	0.02381	0.29905	0.3655	0.0064	Steel	0.32905	0.6281	0.523882

(Sheet 2 of 3)

Table B4 (Concluded)

Mixture ID	w/(c+m)	S/A	Vol. Air (Design) m^3	Vol. Water m^3	Vol. Cement m^3	Vol. Fly Ash m^3	Vol. Fine Aggregate m^3	Vol. Coarse m^3	Vol. Fiber m^3	Type Fiber	Vol. Paste m^3	Vol. Mortar m^3	Paste/ Mortar
DBL-33	0.48	40	0.06	0.157	0.083	0.0208	0.2707	0.406	0.0025	Steel	0.3208	0.5915	0.54235
DBL-66	0.48	40	0.06	0.162	0.0857	0.0214	0.2664	0.3995	0.005	Steel	0.3291	0.5955	0.552645
DBL-85	0.48	40	0.06	0.17	0.0899	0.0225	0.2605	0.3907	0.0064	Steel	0.3424	0.6029	0.567922
DBM-33	0.48	45	0.06	0.162	0.0857	0.0214	0.3008	0.3676	0.0025	Steel	0.3291	0.6299	0.522464
DBM-66	0.48	45	0.06	0.17	0.0899	0.0225	0.2937	0.3589	0.005	Steel	0.3424	0.6361	0.53828
DBM-85	0.48	45	0.06	0.175	0.0926	0.0231	0.2893	0.3536	0.0064	Steel	0.3507	0.64	0.547969
FAL-1.6	0.4	40	0.06	0.147	0.0934	0.0233	0.2701	0.4052	0.001	Polypropylene	0.3237	0.5938	0.545133
FAM-1.6	0.4	45	0.06	0.153	0.0971	0.0243	0.2991	0.3655	0.001	Polypropylene	0.3344	0.6335	0.527861
FBL-1.6	0.48	40	0.06	0.158	0.0836	0.0207	0.2706	0.4059	0.001	Polypropylene	0.3223	0.5929	0.543599
FBM-1.6	0.48	45	0.06	0.166	0.0878	0.022	0.2984	0.3648	0.001	Polypropylene	0.3358	0.6342	0.529486

(Sheet 3 of 3)

Table B5
Phase I Fresh Properties

Mixture ID	Slump mm,	Unit Weight, kg/m³	Air Content, %	Vebe Time, sec	Water Content, kg/m³	Temperature, °C	Comments
ALO	55	2313	6.0	2	143	24.9	Good mix; finished easily
BLO	90	2307	5.7	NA[1]	148	23.9	Good mix; little oversanded
P1AL1.5	45	2320	5.2	3	148	22.4	Good mix; finished easily
P1AL6.25	55	2300	5.8	3	155	23.1	Good mix; finished easily
P1AL15	45	2294	5.5	5	160	23.6	Good mix; finished easily
P1AL20	40	2268	5.6	6	166	22.7	Somewhat harsh; finished ok
P1AL25	25	2281	5.4	7	169	22.5	Harsh; difficult to finish
P1AM6.25	25	2307	5.6	6	148	23.4	Good mix; finished easily
P1AM15	32	2288	5.5	6	156	19.4	Good mix; finished easily
P1AM20	50	2252	6.2	4	170	19.4	Good mix; finished ok
P1AM25	38	2256	6.2	5	172	19.4	Somewhat harsh; finished ok
P1AH20	25	2262	5.6	5	169	19.4	Good mix; finished easily
P1AH25	25	2249	5.6	6	170	23.1	Good mix; finished ok
P1BL1.5	75	2333	4.9	NA	151	24.6	Good mix; finished easily
P1BL6.25	100	2294	5.6	NA	153	20.4	Good mix; finished easily
P1BL15	90	2268	5.3	NA	173	19.7	Good mix; finished ok
P1BL20	100	2249	5	NA	180	23.4	Somewhat harsh; finished ok
P1BL25	85	2230	5.5	NA	187	23.6	Harsh; difficult to finish
P1BM6.25	90	2256	6.4	NA	161	24.3	Good mix; finished easily
P1BM15	95	2249	5.7	NA	173	24.1	Somewhat harsh; finished ok
P1BM20	100	2217	6.3	NA	180	23.9	Somewhat harsh; finished ok
P1BM25	85	2217	5.8	NA	182	24.2	Harsh; difficult to finish
P1BH20	90	2217	6.5	NA	178	22.5	Good mix; finished easily
P1BH25	85	2217	6.2	NA	180	23.0	Good mix; finished easily
P2AL1.5	50	2313	5.7	3	145	23.7	Good mix; finished easily
P2AL6.25	50	2313	5.6	4	150	23.3	Good mix; finished easily
P2AL15	40	2303	5.0	6	155	23.2	Somewhat harsh; finished ok
P2AL20	30	2268	5.4	9	162	22.5	Harsh; difficult to finish
P2AM6.25	30	2319	5.2	5	146	24.4	Good mix; finished easily
P2AM15	55	2262	6.2	3	157	23.3	Good mix; finished easily
P2AM20	50	2281	5.0	4	168	24.9	Somewhat harsh; finished ok
P2AM25	50	2243	5.5	6	170	23.2	Harsh; difficult to finish
P2AH15	40	2281	5.8	5	167	21.8	Good mix; little oversanded
P2AH20	30	2259	5.5	5	167	25.0	Good mix; finished easily

(Continued)

[1] NA - Test result not available; all measurements less than 1 sec.

Table B5 (Concluded)							
Mixture ID	Slump mm,	Unit Weight, kg/m^3	Air Content, %	Vebe Time, sec	Water Content, kg/m^3	Temperature, °C	Comments
P2AH25	50	2259	5.5	5	170	23.3	Good mix; finished ok
P2BL1.5	85	2303	5.7	NA	148	23.3	Good mix; finished easily
P2BL6.25	110	2291	5.9	NA	153	23.3	Good mix; finished easily
P2BL15	110	2268	5.0	NA	178	23.3	Somewhat harsh; finished ok
P2BL20	90	2207	6.5	NA	185	25.0	Harsh; difficult to finish
P2BM6.25	100	2268	6.0	NA	161	24.8	Good mix; little oversanded
P2BM15	90	2265	5.5	NA	175	24.8	Good mix; finished easily
P2BM20	95	2243	6.0	NA	180	25.0	Good mix; finished ok
P2BM25	90	2223	5.9	NA	183	25.0	Somewhat harsh; finished ok
P2BH15	90	2246	5.3	NA	173	23.0	Good mix; little oversanded
P2BH20	90	2227	6.2	NA	175	24.7	Good mix; little oversanded
P2BH25	90	2232	5.8	NA	178	24.1	Good mix; finished easily
DAL33	30	2352	4.7	7	151	21.4	Good mix; finished easily
DAL66	40	2352	4.7	7	157	21.6	Good mix; finished ok
DAL85	30	2384	4.1	6	160	21.3	Good mix; finished ok
DAM33	45	2307	6.2	2	151	21.9	Good mix; finished easily
DAM66	30	2332	5.7	3	151	22.1	Good mix; finished easily
DAM85	40	2326	6.0	4	150	22.1	Good mix; finished easily
DBL33	100	2326	4.9	NA	157	23.3	Good mix; finished easily
DBL66	75	2326	5.2	NA	162	21.1	Good mix; finished easily
DBL85	95	2300	5.7	NA	170	21.6	Good mix; finished easily
DBM33	110	2294	5.6	NA	162	23.3	Good mix; little oversanded
DBM66	110	2268	6.7	NA	170	21.4	Good mix; finished easily
DBM85	95	2268	6.5	NA	175	21.4	Good mix; finished easily
FAL1.6	25	2320	5.1	3	147	22.8	Good mix; finished easily
FAM1.6	45	2313	5.8	4	153	22.8	Good mix; finished easily
FBL1.6	95	2281	5.7	NA	158	22.4	Good mix; finished easily
FBM1.6	75	2275	5.8	NA	166	23.3	Good mix; finished easily

Table B6
Phase II Fresh Properties

Mixture ID	Slump, mm	Unit Weight, kg/m3	Air Content, %	Vebe Time, sec
AHO	40	2,372	5.4	NR[1]
AHO	30	2,316	6.2	NR
AHO	40	2,342	5.3	5
BHO	90	2,274	6.4	NA[2]
BHO	90	2,295	5.8	NA
BHO	75	2,295	5.8	NA
P1AM25	25	2,281	5.2	11
P1AH25	45	2,284	5.8	8
P1BM25	100	2,222	6.3	NA
P1BH25	90	2,222	5.8	NA
P2AM15	25	2,246	5.6	5
P2AM25	20	2,235	5.8	NR
P2AM25	25	2,211	5.8	12
P2AH15	65	2,217	5.6	5
P2AH25	50	2,195	6.0	5
P2AH25	55	2,191	6.3	NR
P2AH25	55	2,204	6.1	6
P2BM15	75	2,255	5.9	NA
P2BM25	90	2,287	4	NA
P2BH1.5	90	2,303	5.7	NA
P2BH1.5	85	2,303	5.7	NA
P2BH6.25	85	2,274	6.4	NA
P2BH6.25	80	2,327	6.4	NA
P2BH15	75	2,258	6.3	NA
P2BH20	90	2,252	6	NA
P2BH25	95	2,242	6	NA
P2BH25	95	2,235	6.3	NA
P2BH25	65	2,527	5.5	NA

[1] NR - Test not run.
[2] NA - Test result not available; all measurements less than 1 second.

Table B7
Hardened Properties, Phase I

Mixture ID	Comp Strength		Flex Strength		Impact	
	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
ALO	34.0	0.8	5.90	0.14	8	3
P2AL-1.5	38.7	1.2	5.81	0.52	15	4
P2AM6.25	37.4	0.6	5.25	0.20	22	8
P2AL6.25	32.0	0.6	5.06	0.18	30	9
P2AH15	39.0	0.8	4.38	0.28	33	11
P2AL15	32.6	0.5	4.88	0.17	31	4
P2AL15	37.3	1.8	5.93	0.11	30	5
P2AH20	40.4	0.4	5.70	0.27	NA	NA
P2AM20	44.2	1.1	4.39	0.25	NA	NA
P2AL20	39.3	0.7	4.40	0.39	51	15
P2AH25	35.4	1.3	5.20	0.32	40	9
P2AM25	39.1	1.9	4.41	0.07	57	17
BLO	33.8	0.6	4.74	0.31	4	1
P2BL1.5	33.8	0.6	4.74	0.31	9	13
P2BM6.25	35.9	0.1	5.20	0.15	NA	NA
P2BL6.25	32.0	1.1	4.86	0.17	31	14
P2BM15	36.2	0.9	4.33	0.23	37	7
P2BM15	37.9	1.6	5.05	0.50	NA	NA
P2BL15	36.9	0.1	5.20	0.22	51	14
P2BH20	31.6	2.5	4.78	0.25	33	6
P2BH20	33.2	0.8	4.78	0.25	NA	NA
P2BM20	37.8	0.5	5.06	0.26	NA	NA
P2BL20	32.4	0.8	4.54	0.22	NA	NA
P2BH25	31.1	2.0	4.98	0.36	57	21
P2BM25	39.8	0.4	4.80	0.32	NA	NA
P1AL1.5	38.8	1.6	4.31	0.15	12	2
P1AM6.25	40.3	2.0	4.46	0.20	20	4
P1AL6.25	35.4	2.1	3.76	0.14	18	3
P1AM15	37.0	2.2	4.50	0.17	26	6
P1AL15	40.0	1.1	4.75	0.18	37	9
P1AH20	38.1	0.5	5.38	0.33	36	7
P1AM20	NA	NA	5.21	0.21	35	9
P1AL20	40.0	0.6	4.33	0.28	30	13
P1AH25	37.8	1.3	5.53	0.03	36	6
P1AM25	39.0	1.3	5.44	0.25	39	15
P1AL25	38.0	2.0	4.96	0.38	34	11

(Continued)

Shaded areas indicate that an outlier was removed from that mixture.

Table B7 (Concluded)

Mixture ID	Comp Strength		Flex Strength		Impact	
	Avg	Std Dev	Avg Flex	Std Dev	Avg	Std Dev
P1BL1.5	36.5	2.1	5.16	0.11	14	5
P1BM6.25	33.6	0.6	5.01	0.26	22	5
P1BL6.25	35.3	1.3	5.25	0.13	22	5
P1BM15	33.6	0.7	5.14	0.23	29	6
P1BL15	33.7	0.5	5.20	0.09	28	7
P1BH20	32.8	0.5	4.94	0.31	34	8
P1BM20	31.6	0.4	4.93	0.31	38	10
P1BL20	33.3	1.3	5.16	0.32	35	4
P1BH25	29.9	1.2	3.74	0.19	33	10
P1BM25	31.2	0.5	4.90	0.23	41	14
P1BL25	33.3	1.2	4.95	0.32	41	11
FAM1.6	41.3	1.0	4.98	0.19	11	4
FAL1.6	36.7	0.6	5.25	0.27	11	3
FBM1.6	32.4	1.0	3.98	0.31	12	4
FBL1.6	34.6	1.1	4.23	0.20	9	3
DAM33	36.8	2.2	4.63	0.26	35	12
DAL33	38.9	1.8	4.39	0.14	37	13
DAM66	38.7	0.8	5.18	0.23	52	17
DAL66	38.8	0.5	5.26	0.48	66	9
DBM85	36.6	1.6	5.28	0.38	47	13
DAL85	39.8	0.3	6.23	0.59	93	29
DBM33	32.1	0.9	4.34	0.23	38	14
DBL33	33.9	1.4	4.63	0.10	34	8
DBM66	34.1	0.9	4.55	0.28	59	25
DBL66	40.6	0.4	4.82	0.32	67	24
DBM85	32.4	1.9	4.90	0.39	65	12
DBL85	32.1	0.5	5.66	0.32	58	21

Table B8
Test Results, Phase II

Mixture ID	7-day Tests						14-day Tests		28-day Tests			
	Comp Strength		Flex Strength		Impact		F&T Durability		Comp Strength		Flex Strength	
	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
AHO	NA	NA	NA	NA	NA	NA	94	1	45.2	0.8	NA	NA
AHO	NA	NA	NA	NA	NA	NA	87	3	38.1	1.9	NA	NA
AHO	34.1	0.8	4.22	0.14	4	2	90	4	4.50	2.5	4.08	0.17
P2AM15	30.7	0.6	4.14	0.10	NA	NA	NA	NA	42.4	1.4	4.91	0.21
P2AH15	28.6	0.6	3.81	0.26	NA	NA	NA	NA	39.7	0.0	4.64	0.54
P2AM25	NA	NA	NA	NA	NA	NA	NA	NA	39.3	1.8	NA	NA
P2AM25	NA	NA	NA	NA	NA	NA	NA	NA	40.1	1.0	4.48	0.25
P2AH25	28.7	1.1	3.86	0.38	NA	NA	NA	NA	38.1	1.9	NA	NA
P2AH25	NA	NA	NA	NA	NA	NA	87	3	36.8	1.7	NA	NA
P2AH25	NA	NA	NA	NA	46	12	81	6	35.4	0.3	4.55	0.19
BHO	24.0	0.0	3.51	0.15	NA	NA	88	2	36.5	0.8	NA	NA
BHO	NA	NA	NA	NA	NA	NA	88	4	34.2	2.1	3.87	0.03
BHO	23.5	0.7	3.33	0.28	5	1	86	7	32.4	0.4	NA	NA
P2BH1.5	NA	NA	NA	NA	NA	NA	90	1	34.6	0.6	NA	NA
P2BH1.5	NA	NA	NA	NA	NA	NA	NA	NA	34.6	0.6	NA	NA
P2BH6.25	NA	NA	NA	NA	NA	NA	NA	NA	33.8	0.7	NA	NA
P2BM15	20.7	1.0	3.56	0.17	NA	NA	NA	NA	30.0	1.6	4.45	0.25
P2BH15	23.7	0.7	3.48	0.20	NA	NA	NA	NA	35.5	0.4	4.46	0.34
P2BH20	NA	NA	NA	NA	NA	NA	NA	NA	32.5	0.5	NA	NA
P2BM25	24.5	0.6	3.76	0.09	NA	NA	NA	NA	33.7	0.6	4.48	0.28
P2BH25	NA	NA	NA	NA	NA	NA	87	1	32.9	0.2	NA	NA
P2BH25	NA	NA	NA	NA	NA	NA	91	1	33.8	0.6	NA	NA
P2BH25	23.9	0.2	3.45	0.12	66	13	98	1	32.8	0.6	5.60	0.42
P1AM25	35.0	0.2	4.65	0.15	NA	NA	NA	NA	44.2	0.8	5.63	0.32
P1AH25	31.2	0.6	3.89	0.22	NA	NA	NA	NA	38.1	1.8	4.85	0.27
P1BM25	19.5	0.2	2.60	0.35	NA	NA	NA	NA	26.8	0.9	3.40	0.04
P1BH25	21.3	0.3	3.20	0.15	NA	NA	NA	NA	29.9	0.5	4.11	0.31

(Continued)

Shaded areas indicate that an outlier was removed from that mixture.

Table B8 (Concluded)

	28-day Tests				90-day Tests									
	Impact		Modulus		Cl Perm		Comp Strength		Flex Strength		Impact		Cl Perm	
Mixture ID	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
AHO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AHO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AHO	4	1	NA	NA	3,640	530	50.7	2.3	6.03	0.43	NA	NA	2,158	204
P2AM15	68	28	NA	NA	NA	NA	48.6	1.8	5.01	0.14	81	17	NA	NA
P2AH15	62	22	NA	NA	NA	NA	45.0	0.6	4.88	0.09	79	24	NA	NA
P2AM25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2AM25	124	51	NA	NA	NA	NA	44.2	2.8	4.98	0.23	177	66	NA	NA
P2AH25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2AH25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2AH25	63	17	30.7	0.3	5,306	1,361	38.8	1.2	4.88	0.17	87	38	3,339	1,108
BHO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BHO	5	1	36.5	4.9	NA	NA	39.2	0.2	4.87	0.30	NA	NA	NA	NA
BHO	NA	NA	NA	NA	5,601	711	NA	NA	NA	NA	NA	NA	2,867	892
P2BH1.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2BH1.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2BH6.25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2BM15	37	12	NA	NA	NA	NA	35.9	1.1	4.81	0.13	69	23	NA	NA
P2BH15	82	28	NA	NA	NA	NA	40.9	1.1	4.80	0.20	132	42	NA	NA
P2BH20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2BM25	136	67	NA	NA	NA	NA	NA	NA	5.50	0.25	NA	NA	NA	NA
PBH25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2BH25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P2BH25	79	26	32.9	1.1	5,682	734	36.5	1.0	4.33	0.15	77	29	3,237	615
P1AM25	99	47	NA	NA	NA	NA	48.1	2.7	6.35	0.15	93	16	NA	NA
P1AH25	62	18	NA	NA	NA	NA	43.9	0.6	6.08	0.20	70	17	NA	NA
P1BM25	55	16	NA	NA	NA	NA	31.8	0.7	4.68	0.08	66	17	NA	NA
P1BH25	62	11	29.2	0.6	NA	NA	35.6	1.2	4.93	0.09	59	15	NA	NA

Table B9
Summary of Original Toughness Data, Phase I

Mixture ID	I30	I50	JCI	EAR
P2BM6.25	17.09	19.41	27.86	0.22
P2BM15	15.22	21.11	37.09	0.55
P2BM20	15.81	23.15	47.69	0.70
P2BM25	17.03	26.27	55.63	0.92
P2BL1.5	16.11	26.47	58.24	0.08
P2BL6.25	16.48	27.08	45.72	0.18
P2BL15	21.41	32.32	61.70	0.65
P2BL20	13.29	19.03	35.19	0.55
P2BL15	20.08	26.56	43.24	0.65
P2BH20	15.60	23.31	45.46	0.74
P2BH25	21.79	31.15	61.99	0.88
P2AM6.25	16.58	27.23	47.18	0.23
P2AM15	19.31	29.16	45.95	0.48
P2AM20	18.19	27.20	58.35	1.06
P2AM25	17.87	28.27	56.56	0.98
P2AL6.25	16.26	26.58	46.97	0.21
P2AL15	18.11	29.73	52.39	0.45
P2AL20	19.59	29.22	56.45	1.03
P2AH15	18.20	24.56	42.61	0.61
P2AH20	14.63	19.97	43.42	0.56
P2AH25	22.00	30.93	59.10	0.78
P1BM6.25	15.99	26.17	44.04	0.16
P1BM15	18.32	28.17	46.45	0.46
P1BM20	21.10	28.71	49.77	0.56
P1BM25	20.53	27.21	48.51	0.55
P1BL6.25	16.57	27.14	48.45	0.19
P1BL15	13.87	21.20	45.06	0.32
P1BL20	19.90	27.18	47.33	0.51
P1BL25	20.58	28.47	50.38	0.68
P1BH20	19.78	26.72	45.49	0.52
P1BH25	19.58	28.96	50.01	0.98

(Continued)

Shaded areas indicate that an outlier was removed from that mixture.

Table B9 (Concluded)				
Mixture ID	I30	I50	JCI	EAR
P1AM6.25	17.19	22.74	34.90	0.33
P1AM15	17.11	23.25	44.76	0.67
P1AM20	18.00	24.97	45.11	0.44
P1AM25	19.76	25.29	48.65	0.55
P1AL1.5	15.97	26.25	37.38	0.18
P1AL6.25	18.19	23.19	32.72	0.47
P1AL15	19.03	25.59	49.02	0.72
P1AL20	18.71	26.72	49.69	0.97
P1AL25	17.83	28.05	64.06	1.07
P1AH15	17.82	23.79	42.46	0.60
P1AH20	19.89	30.18	49.49	0.52
P1AH25	21.58	28.71	56.65	0.63
FBM1.6	20.96	33.68	46.01	0.12
FBL1.6	16.46	27.04	52.99	0.08
FAM1.6	16.39	26.57	48.19	0.29
FAL1.6	16.46	27.07	62.38	0.06
DBM33	21.24	33.70	66.85	1.30
DBM66	12.10	40.41	83.58	1.59
DMB85	30.40	51.69	113.19	1.94
DBL33	22.74	34.79	72.06	1.29
DBL66	27.95	47.32	104.45	1.77
DBL85	33.91	57.78	127.78	2.19
DAM33	20.74	32.17	65.84	1.21
DAM66	27.44	45.69	101.27	1.63
DAM85	7.64	12.63	27.96	0.46
DAL33	18.85	29.05	59.39	1.11
DAL66	24.80	41.32	100.26	1.62
DAL85	31.49	54.08	127.02	2.07

Table B10
Summary of Toughness Data, Modified by Procedure A, Phase I

Mixture ID	I30		I50		JCI		EAR	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
P2BM6.25	4.38	1.1	6.67	1.6	14.56	3.8	0.22	0.06
P2BM15	10.33	1.2	16.22	1.5	21.38	18.6	0.54	0.01
P2BM20	12.71	2.0	20.05	3.0	44.15	5.9	0.71	0.12
P2BM25	14.50	2.5	23.28	4.2	53.41		0.92	0.09
P2BL6.25	1.58	0.4	1.80	0.7	5.17	2.7	0.12	0.06
P2BL15	11.15	1.4	18.02	2.5	41.27	4.9	0.66	0.09
P2BH15	10.71	1.1	16.66	1.8	31.72		0.64	0.10
P2BH20	12.97	2.3	20.67	3.8	42.87	7.5	0.75	0.14
P2BH25	15.29	1.5	24.64	2.0	54.33	2.0	0.89	0.05
P2AM6.25	2.01	0.4	2.50	0.7	7.83	3.2	0.15	0.05
P2AM15	7.28	2.5	11.58	4.2	26.48	6.2	0.45	0.11
P2AM20	11.37	1.3	20.38	2.3	53.71		1.01	0.09
P2AM25	11.85	2.4	20.82	5.2	49.03	13.8	0.96	0.27
P2AL6.25	2.47	0.2	20.82	0.7	9.52	2.2	0.96	0.06
P2AL15	4.96		8.12		25.98		0.48	
P2AL20	7.97	2.0	12.74	2.6	30.53	5.6	0.54	0.06
P2AH15	8.72	1.6	16.63		32.53	8.2	0.60	0.17
P2AH20	9.90	1.5	15.67	2.3	38.18	5.9	0.56	0.08
P2AH25	11.62	1.8	18.97	2.8	43.68	5.9	0.72	0.08
P1BL15	6.55	1.9	10.35	3.0	25.24	6.4	0.41	0.10
P1BL20	9.53	2.8	15.21	4.0	33.63	5.6	0.52	0.10
P1BL25	13.43	2.3	20.90	3.1	42.41	6.1	0.70	0.13
P1BH20	8.76	1.5	14.47	2.3	32.17	4.5	0.52	0.1
P1BH25	13.89	4.1	22.88	6.6	43.82	10.9	0.96	0.36
P1AM6.25	3.88	0.9	6.10	1.4	16.21	2.0	0.31	0.04
P1AM15	8.85		15.86		35.18		0.68	

(Continued)

Shaded areas indicate that an outlier was removed from that mixture.

Table B10 (Concluded)								
	I30		I50		JCI		EAR	
Mixture ID	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
P1AM20	5.89	2.0	9.72	3.3	25.55	4.8	0.42	0.09
P1AM25	9.94	1.6	16.05	2.1	37.82	3.5	0.56	0.05
P1AL1.5	1.75	0.2	2.04		5.50	1.2	0.12	0.03
P1AL6.25	5.73	1.0	10.02	1.2	20.72	1.6	0.45	0.04
P1AL15	10.19	2.7	16.14	3.6	38.37	5.9	0.69	0.14
P1AL20	12.58	1.0	21.29	1.9	62.42	8.8	0.94	0.06
P1AL25	14.63	1.1	24.83	1.9	60.02	3.9	1.08	0.12
P1AH20	7.88		12.87		31.02		0.50	
P1AH25	12.05		18.20		44.92		0.65	
FBM1.6	0		0		0		0	
FBL1.6	0		0		0		0	
FBH1.6	0		0		0		0	
FAM1.6	2.02	0.5	2.61	0.8	6.89	3.2	0.14	0.08
FAL1.6	9.22	8.9	14.79	15.1	35.59	37.8	0.03	0.04
DBM33	17.85	3.5	30.31	5.9	63.52	11.2	1.31	0.21
DBM66	Use Original Data							
DMB85	Use Original Data							
DBL33	16.82	4.3	28.87	8.0	66.52	18.1	1.33	0.34
DBL66	Use Original Data							
DBL85	Use Original Data							
DAM33	15.62	4.1	27.05	6.6	60.54	10.6	1.20	0.24
DAM66	Use Original Data							
DAM85	Use Original Data							
DAL33	14.30		24.50		55.22		1.09	
DAL66	Use Original Data							
DAL85	Use Original Data							

Table B11
Summary of Toughness Data Modified by Procedure A, Phase II, 28-day

Mixture ID	I30		I50		JCI		EAR	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
AHO	0	0	0	0	0	0	0	0
P2AH15	13.20	0.6	21.70	1.2	48.44	7.4	0.94	0.08
P2AH25	20.40	1.8	33.43	2.9	71.03	7.6	1.37	0.17
P2AM15	15.49	4.8	23.41	5.3	51.02	4.2	0.92	0.08
P2AM25	20.25	1.7	33.35	0.5	74.05	6.6	1.44	0.06
BHO	0	0	0	0	0	0	0	0
P2BH15	17.40	4.6	28.10	5.0	57.96	0.4	1.23	0.12
P2BM15	12.33	2.5	19.96	3.7	43.00	4.9	0.89	0.19
P2BM25	24.20	1.6	40.01	0.6	84.00	2.8	1.91	0.21
P1AM25	19.60	2.0	32.67	0.5	72.60	1.4	1.24	0.11
P1BH25	19.30	1.4	31.50	2.4	57.75	5.2	1.29	0.12

Table B12
Aggregate Properties, Producer A

Sieve Size	Percent Passing: Coarse Aggregate 970463	Percent Passing: Fine Aggregate 970462
25.0 mm	95	
19.0 mm	81	
12.5 mm	52	
9.5 mm	33	
4.75 mm	5	93
2.36 mm		82
1.18 mm		72
600 μm		55
300 μm		14
150 μm		1
Specific Gravity	2.55	2.59
Absorption, %	1.97	0.65

Table B13
Aggregate Properties, Producer B

Sieve Size	Percent Passing: Coarse Aggregate 970463	Percent Passing: Fine Aggregate 970462
25.0 mm	94	
19.0 mm	79	
12.5 mm	55	
9.5 mm	42	
4.75 mm	11	96
2.36 mm		89
1.18 mm		83
600 μm		72
300 μm		19
150 μm		1
Specific Gravity	2.56	2.58
Absorption, %	1.81	0.83

Table B14
Chemical and Physical Properties of Portland Cement, Whitetopping Project, Procedure A

Chemical Analysis	Results	Retest	ASTM C 150 Spec Limits "Type I"
SiO_2, %	21.3		-
Al_2O_3, %	4.0		-
Fe_2O_3, %	2.9		-
CaO, %	63.1		-
MgO, %	4.1		6.0 max
SO_3, %	2.7		3.0, 3.5 max[a]
Loss on ignition, %	1.1		3.0 max
Insoluble residue, %	0.03		0.75 max
Na_2O, %	0.18		-
K_2O, %	0.88		-
Alkalies-total as Na_2O, %	0.76		0.60 max
TiO_2, %	0.25		-
P_2O_5, %			-
C_3A, %	7		-
C_3S, %	55		-
C_2S, %	20		-
C_4AF, %	9		-
Physical Tests			
Heat of hydration, 7-day, cal/g	-		-
Surface area, m^2/kg (air permeability)	364		280 min
Autoclave expansion, %	0.08		0.80 max
Initial set, min. (Gillmore)	150		60 min
Final set, min. (Gillmore)	290		600 max
Air content, %	7		12 max
Compressive strength, 3-day, psi	3,430		1,740 min
Compressive strength, 7-day, psi	4,200		2,760 min
False set (final penetration), %			50 min

REMARKS: [a]See ASTM C 150 (ASTM 1995j). (See References at end of main text.)

Table B15
Physical Properties of Fly Ash, Whitetopping Project, Procedure A

Chemical Analysis	Results	Retest	ASTM C 618 Spec Limits "Class F"
SiO_2, %	33.5		-
Al_2O_3, %	20.6		-
Fe_2O_3, %	5.9		-
Sum, %	60.0		70.0 min
CaO, %	-		-
R Factor	-		a
MgO, %	6.1		-
SO_3, %	2.2		5.0, 4.0[a] max
Moisture content, %	0.2		3.0 max
Loss on ignition, %	0.4		6.0, 2.5[a] max
Available alkalies (28-day), %			1.5 max
Physical Tests			
Fineness (45 micrometre, % retained	19		34 max
Fineness variation, %	-		5 max
Water requirement, %	95		105 max
Density, Mg/m^3	2.59		-
Density variation, %	-		5 max
Autoclave expansion, %	0.12		0.80 max
Strength activity index w/cement, 7-d, %	98		75[b] min
Strength activity index w/cement, 28-d, %	107		75[b] min

REMARKS: [a]Only applies to Bureau of Reclamation projects.
[b]Note change in testing (ASTM C 618 (ASTM 1995r)).

Table B16
Physical Properties of Portland Cement, Whitetopping Project, Procedure B

Chemical Analysis	Results	Retest	ASTM C 150 Spec Limits "Type I"
SiO_2, %	21.0		-
Al_2O_3, %	4.1		-
Fe_2O_3, %	4.0		-
CaO, %	63.8		-
MgO, %	1.1		6.0 max
SO_3, %	2.7		3.0, 3.5 max[a]
Loss on ignition, %	1.6		3.0 max
Insoluble residue, %	0.12		0.75 max
Na_2O, %	0.10		-
K_2O, %	0.47		-
Alkalies-total as Na_2O, %	0.41		0.60 max
TiO_2, %	0.28		-
P_2O_5, %	-		-
C_3A, %	5		-
C_3S, %	57		-
C_2S, %	17		-
C_4AF, %	12		-
Physical Tests			
Heat of hydration, 7-day, cal/g	-		-
Surface area, m^2/kg (air permeability)	385		280 min
Autoclave expansion, %	-0.01		0.80 max
Initial set, min. (Gillmore)	205		60 min
Final set, min. (Gillmore)	315		600 max
Air content, %	6		12 max
Compressive strength, 3-day, psi	3,370		1,740 min
Compressive strength, 7-day, psi	4,340		2,760 min
False set (final penetration), %	81		50 min

REMARKS: [a]See ASTM C 150 (ASTM 1995j).

Table B17
Chemical and Physical Properties of Fly Ash, Whitetopping Project, Procedure B

Chemical Analysis	Results	Retest	ASTM C 618 Spec Limits "Class F"
SiO_2, %	53.1		-
Al_2O_3, %	23.5		-
Fe_2O_3, %	14.5		-
Sum, %	91.1		70.0 min
CaO, %			-
R Factor	-		a
MgO, %	0.5		-
SO_3, %	0.7		5.0, 4.0[a] max
Moisture content, %	0.4		3.0 max
Loss on ignition, %	-		6.0, 2.5[a] max
Available alkalies (28-day), %			1.5 max
Physical Tests			
Fineness (45 micrometre, % retained	33		34 max
Fineness variation, %	-		5 max
Water requirement, %	99		105 max
Density, Mg/m^3	2.43		-
Density variation, %	-		5 max
Autoclave expansion, %	-0.04		0.80 max
Pozzolanic activity w/lime, psi	-		
Strength activity index w/cement, 7-d, %	75		75[b] min
Strength activity index w/cement, 28-d, %	93		75[b] min

REMARKS: [a]Only applies to Bureau of Reclamation projects.
[b]Note change in testing (ASTM C 618 (ASTM 1995r)).

Appendix C
Statistical Information

Table C1
Confounding Data, Phase I, Polyolefin Type 25/38 Fibers

	w/(c+m)	S/A	Fiber Volume	Air Content	Mortar Content	p/m
w/(c+m)	1					
S/A	1.16E-17	1				
Fiber Volume	1.25E-17	0.467514	1			
Air Content	0.070172	0.551425	0.202401285	1		
Mortar Content	-0.04539	0.954588	0.688402869	0.524113	1	
p/m	-0.11211	-0.42936	0.563626079	-0.2685	0.14362	1

Table C2
Confounding Data, Phase I, Polyolefin Type 50/63 Fibers

	w/(c+m)	S/A	Fiber Volume	Air Content	Mortar Content	p/m
w/(c+m)	1					
S/A	0.054957	1				
Fiber Volume	0.027703	0.582176	1			
Air Content	0.270064	0.002584	-0.111024	1		
Mortar Content	0.037522	0.967846	0.7390574	-0.02431	1	
p/m	-0.08527	-0.43818	0.4203926	0.10674	-0.20166	1

Table C3
Phase I, Steel Fibers

	w/(c+m)	S/A	Fiber Volume	Air Content	Mortar Content	p/m
w/(c+m)	1					
S/A	6.01E-17	1				
Fiber Volume	4.2E-17	0.259317	1			
Air Content	0.288547	0.683603	-0.03842	1		
Mortar Content	-0.01008	0.944666	0.48613	0.58153	1	
p/m	-0.00877	-0.58991	0.493482	-0.53015	-0.30457	1

Table C4
Two-Way Analysis of Variance, Phase I Impact Data

Two Way Analysis of Variance Wednesday, March 25, 1998, 17:35:57

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: Impact

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	5333.027	5333.027	54.983	<0.001
Fiber load	5	95544.220	19108.844	197.011	<0.001
Fiber type x Fiber load	5	2752.417	550.483	5.675	<0.001
Residual	614	59554.090	96.994		
Total	625	164757.580	263.612		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber load. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber load is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber load is present. There is a statistically significant interaction between Fiber type and Fiber load. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 1.000
Power of performed test with alpha = 0.0500: for Fiber load : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber load : 0.983

Least square means for Fiber type

Group	Mean	SEM
P1	23.295	0.543
P2	29.672	0.667

Least square means for Fiber load

Group	Mean	SEM
0.000	5.536	1.140
1.500	13.230	1.305
6.250	23.885	0.977
15.000	33.261	0.861
20.000	38.527	1.053
25.000	44.463	0.922

Least square means for Fiber type x Fiber load

Group	Mean	SEM
P1 x 0.000	5.250	1.316
P1 x 1.500	12.321	1.861
P1 x 6.250	20.133	1.271
P1 x 15.000	30.133	1.271

(Sheet 1 of 4)

Table C4 (Continued)

P1 x 20.000	34.674	1.044	P1 x 25.000	37.258	1.044
P2 x 0.000	5.821	1.861			
P2 x 1.500	14.138	1.829			
P2 x 6.250	27.636	1.485			
P2 x 15.000	36.389	1.161			
P2 x 20.000	42.379	1.829			
P2 x 25.000	51.667	1.520			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	6.377	2	10.486	Yes

Comparisons for factor: **Fiber load**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 0.000	38.927	6	37.555	Yes
25.000 vs. 1.500	31.233	6	27.650	Yes
25.000 vs. 6.250	20.578	6	21.661	Yes
25.000 vs. 15.000	11.201	6	12.560	Yes
25.000 vs. 20.000	5.936	6	5.999	Yes
20.000 vs. 0.000	32.991	6	30.069	Yes
20.000 vs. 1.500	25.297	6	21.339	Yes
20.000 vs. 6.250	14.642	6	14.414	Yes
20.000 vs. 15.000	5.266	6	5.476	Yes
15.000 vs. 0.000	27.725	6	27.453	Yes
15.000 vs. 1.500	20.031	6	18.124	Yes
15.000 vs. 6.250	9.376	6	10.181	Yes
6.250 vs. 0.000	18.349	6	17.283	Yes
6.250 vs. 1.500	10.655	6	9.244	Yes
1.500 vs. 0.000	7.694	6	6.281	Yes

The difference in the mean values among the different levels of Fiber load evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber load within P1**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 0.000	32.008	6	26.947	Yes
25.000 vs. 1.500	24.937	6	16.526	Yes
25.000 vs. 6.250	17.125	6	14.722	Yes
25.000 vs. 15.000	7.125	6	6.125	Yes
25.000 vs. 20.000	2.584	6	2.475	No
20.000 vs. 0.000	29.424	6	24.772	Yes
20.000 vs. 1.500	22.353	6	14.813	Yes
20.000 vs. 6.250	14.541	6	12.500	Yes
20.000 vs. 15.000	4.541	6	3.904	Yes
15.000 vs. 0.000	24.883	6	19.231	Yes
15.000 vs. 1.500	17.812	6	11.176	Yes
15.000 vs. 6.250	10.000	6	7.865	Yes
6.250 vs. 0.000	14.883	6	11.502	Yes
6.250 vs. 1.500	7.812	6	4.901	Yes
1.500 vs. 0.000	7.071	6	4.387	Yes

(Sheet 2 of 4)

Table C4 (Continued)

The difference in the mean values among the different levels of Fiber load evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber load within P2**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	45.845	6	26.983	Yes
25.000 vs. 1.500	37.529	6	22.320	Yes
25.000 vs. 6.250	24.030	6	15.996	Yes
25.000 vs. 15.000	15.278	6	11.299	Yes
25.000 vs. 20.000	9.287	6	5.524	Yes
20.000 vs. 0.000	36.558	6	19.814	Yes
20.000 vs. 1.500	28.241	6	15.442	Yes
20.000 vs. 6.250	14.743	6	8.851	Yes
20.000 vs. 15.000	5.990	6	3.911	Yes
15.000 vs. 0.000	30.567	6	19.708	Yes
15.000 vs. 1.500	22.251	6	14.528	Yes
15.000 vs. 6.250	8.753	6	6.568	Yes
6.250 vs. 0.000	21.815	6	12.958	Yes
6.250 vs. 1.500	13.498	6	8.104	Yes
1.500 vs. 0.000	8.317	6	4.507	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 0**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	0.571	2	0.355	No

The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 1.5**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	1.817	2	0.985	No

The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 6.25**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	7.503	2	5.428	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	6.256	2	5.139	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 20 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

(Sheet 3 of 4)

Table C4 (Concluded)

Comparisons for factor: **Fiber type within 20**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	7.705	2	5.175	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference ($P = <0.001$).

Comparisons for factor: **Fiber type within 25**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	14.408	2	11.052	Yes

(Sheet 4 of 4)

Table C5
Two-Way Analysis of Variance, Phase II Impact Data

Two Way Analysis of Variance **Wednesday, March 25, 1998, 17:46:23**

Data source: Data 1 in Notebook

General Linear Model (No Interactions)

Dependent Variable: Impact

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	28910.246	28910.246	21.225	<0.001
Fiber load	2	178069.633	89034.816	65.367	<0.001
Residual	198	269692.980	1362.086		
Total	201	448020.955	2228.960		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber load. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber load is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.0500: for Fiber type : 0.998
Power of performed test with alpha = 0.0500: for Fiber load : 1.000

Least square means for Fiber type

Group	Mean	SEM
P1	24.920	6.439
P2	56.225	3.267

Least square means for Fiber load

Group	Mean	SEM
25.000	85.398	3.398
0.000	-10.974	7.758
15.000	47.294	5.989

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: Fiber type

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	31.305	2	6.132	Yes

Comparisons for factor: Fiber load

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	96.372	3	16.092	Yes
25.000 vs. 15.000	38.104	3	7.826	Yes
15.000 vs. 0.000	58.268	3	8.408	Yes

Table C6
Two-Way Analysis of Variance, Phase I Versus Phase II Impact Data

Two Way Analysis of Variance Wednesday, March 25, 1998, 18:22:35

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: Impact

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	331.037	331.037	0.449	0.503
Phase #	1	201906.496	201906.496	273.759	<0.001
Fiber type x Phase #	1	2171.752	2171.752	2.945	0.087
Residual	824	607728.710	737.535		
Total	827	850418.314	1028.317		

The difference in the mean values among the different levels of Fiber type is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Phase #. There is not a statistically significant difference (p = 0.503).

The difference in the mean values among the different levels of Phase # is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type does not depend on what level of Phase # is present. There is not a statistically significant interaction between Fiber type and Phase #. (P = 0.087)

Power of performed test with alpha = 0.0500: for Fiber type : 0.0500
Power of performed test with alpha = 0.0500: for Phase # : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Phase # : 0.269

Least square means for Fiber type

Group	Mean	SEM
P1	48.036	1.899
P2	49.629	1.430

Least square means for Phase #

Group	Mean	SEM
I	29.164	1.113
II	68.502	2.101

Least square means for Fiber type x Phase #

Group	Mean	SEM
P1 x I	26.327	1.390
P1 x II	69.746	3.536
P2 x I	32.000	1.739
P2 x II	67.259	2.271

All Pairwise Multiple Comparison Procedures (Tukey Test):

(Sheet 1 of 4)

Table C6 (Continued)

Comparisons for factor: **Fiber type**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	1.593	2	0.947	No

Comparisons for factor: **Phase #**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
II vs. I	39.339	2	23.399	Yes

(Sheet 2 of 4)

Table C6 (Continued)

Two Way Analysis of Variance Wednesday, March 25, 1998, 18:27:01

Data source: Data 1 in Notebook

General Linear Model (No Interactions)

Dependent Variable: Impact

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber load	5	213636.989	42727.398	87.887	<0.001
Phase #	1	120583.094	120583.094	248.029	<0.001
Residual	821	399141.546	486.165		
Total	827	850418.314	1028.317		

The difference in the mean values among the different levels of Fiber load is greater than would be expected by chance after allowing for effects of differences in Phase #. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Phase # is greater than would be expected by chance after allowing for effects of differences in Fiber load. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.0500: for Fiber load : 1.000
Power of performed test with alpha = 0.0500: for Phase # : 1.000

Least square means for Fiber load

Group	Mean	SEM
0.000	13.097	2.142
1.500	28.939	3.086
6.250	39.001	2.381
15.000	48.647	1.658
20.000	52.261	2.261
25.000	63.321	1.398

Least square means for Phase #

Group	Mean	SEM
I	25.184	0.918
II	56.572	1.861

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber load**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	50.225	6	27.765	Yes
25.000 vs. 1.500	34.382	6	14.352	Yes
25.000 vs. 6.250	24.320	6	12.457	Yes
25.000 vs. 15.000	14.674	6	9.569	Yes
25.000 vs. 20.000	11.060	6	5.883	Yes
20.000 vs. 0.000	39.165	6	17.782	Yes
20.000 vs. 1.500	23.322	6	8.622	Yes

(Sheet 3 of 4)

Table C6 (Concluded)

20.000 vs. 6.250	13.260	6	5.711	Yes
20.000 vs. 15.0003.614		6	1.823	
No				
15.000 vs. 0.000	35.551	6	18.561	Yes
15.000 vs. 1.500	19.708	6	7.957	Yes
15.000 vs. 6.250	9.646	6	4.702	Yes
6.250 vs. 0.000	25.905	6	11.439	Yes
6.250 vs. 1.500	10.062	6	3.651	Yes
1.500 vs. 0.000	15.842	6	5.964	Yes

Comparisons for factor: **Phase #**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
II vs. I	31.387	2	21.393	Yes

(Sheet 4 of 4)

Table C7
Two-Way Analysis of Variance, Phase I, Modified Data, I30

Two Way Analysis of Variance — Tuesday, February 17, 1998, 16:48:16

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: I30

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	94.880	94.880	7.616	0.007
Fiber amount	5	3825.170	765.034	61.406	<0.001
Fiber type x Fiber amount	5	191.633	38.327	3.076	0.011
Residual	151	1881.250	12.459		
Total	162	6053.815	37.369		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = 0.007). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = 0.011)

Power of performed test with alpha = 0.0500: for Fiber type : 0.733
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 0.676

Least square means for Fiber type

Group	Mean	SEM
P1	7.828	0.425
P2	6.175	0.422

Least square means for Fiber amount

Group	Mean	SEM
0.000	3.053E-016	0.943
1.500	0.438	0.882
6.250	5.512	0.707
15.000	10.246	0.622
20.000	11.857	0.558
25.000	13.957	0.603

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P1 x 0.000	5.933E-016	1.334
P1 x 1.500	0.876	1.248
P1 x 6.250	8.534	1.019

(Sheet 1 of 4)

Table C7 (Continued)

P1 x 15.000	11.510	0.943	P1 x 20.000	11.562	0.789
P1 x 25.000	14.486	0.789			
P2 x 0.000	1.735E-017	1.334			
P2 x 1.500	2.394E-016	1.248			
P2 x 6.250	2.491	0.979			
P2 x 15.000	8.982	0.810			
P2 x 20.000	12.151	0.789			
P2 x 25.000	13.427	0.911			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	1.653	2	3.903	Yes

Comparisons for factor: **Fiber amount**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 0.000	13.957	6	17.631	Yes
25.000 vs. 1.500	13.519	6	17.890	Yes
25.000 vs. 6.250	8.444	6	12.858	Yes
25.000 vs. 15.000	3.711	6	6.061	Yes
25.000 vs. 20.000	2.100	6	3.615	No
20.000 vs. 0.000	11.857	6	15.298	Yes
20.000 vs. 1.500	11.418	6	15.466	Yes
20.000 vs. 6.250	6.344	6	9.965	Yes
20.000 vs. 15.000	1.611	6	2.727	No
15.000 vs. 0.000	10.246	6	12.826	Yes
15.000 vs. 1.500	9.808	6	12.850	Yes
15.000 vs. 6.250	4.733	6	7.113	Yes
6.250 vs. 0.000	5.512	6	6.615	Yes
6.250 vs. 1.500	5.074	6	6.348	Yes
1.500 vs. 0.000	0.438	6	0.480	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 0.000	14.486	6	13.216	Yes
25.000 vs. 1.500	13.610	6	13.035	Yes
25.000 vs. 6.250	5.952	6	6.531	Yes
25.000 vs. 15.000	2.976	6	3.422	No
25.000 vs. 20.000	2.924	6	3.705	No
20.000 vs. 0.000	11.562	6	10.549	Yes
20.000 vs. 1.500	10.686	6	10.234	Yes
20.000 vs. 6.250	3.028	6	3.322	No
20.000 vs. 15.000	0.0520	6	0.0598	No
15.000 vs. 0.000	11.510	6	9.962	Yes
15.000 vs. 1.500	10.634	6	9.613	Yes
15.000 vs. 6.250	2.976	6	3.031	No
6.250 vs. 0.000	8.534	6	7.190	Yes
6.250 vs. 1.500	7.658	6	6.722	Yes
1.500 vs. 0.000	0.876	6	0.678	No

(Sheet 2 of 4)

Table C7 (Continued)

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P2**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 0.000	13.427	6	11.753	Yes
25.000 vs. 1.500	13.427	6	12.288	Yes
25.000 vs. 6.250	10.937	6	11.564	Yes
25.000 vs. 15.000	4.446	6	5.157	Yes
25.000 vs. 20.000	1.276	6	1.497	No
20.000 vs. 0.000	12.151	6	11.086	Yes
20.000 vs. 1.500	12.151	6	11.638	Yes
20.000 vs. 6.250	9.660	6	10.864	Yes
20.000 vs. 15.000	3.169	6	3.964	No
15.000 vs. 0.000	8.982	6	8.139	Yes
15.000 vs. 1.500	8.982	6	8.538	Yes
15.000 vs. 6.250	6.491	6	7.225	Yes
6.250 vs. 0.000	2.491	6	2.129	No
6.250 vs. 1.500	2.491	6	2.221	No
1.500 vs. 0.000	2.220E-016	6	1.719E-016	No

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is greater than would be expected by chance. There is a statistically significant difference (P = 0.002).

Comparisons for factor: **Fiber type within 1.5**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	0.876	2	0.702	No

The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 6.25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	6.043	2	6.049	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	2.528	2	2.876	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 20 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 20**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	0.589	2	0.746	No

(Sheet 3 of 4)

Table C7 (Concluded)

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	1.059	2	1.242	No

(Sheet 4 of 4)

Table C8
Two-Way Analysis of Variance, Phase I, Modified Data, I50

Two Way Analysis of Variance Tuesday, February 17, 1998, 18:22:25

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: I50

Normality Test: Failed (P = 0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	163.478	163.478	6.482	0.012
Fiber amount	5	9620.700	1924.140	76.296	<0.001
Fiber type x Fiber amount	5	782.259	156.452	6.204	<0.001
Residual	148	3732.489	25.220		
Total	159	14397.086	90.548		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = 0.012). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 0.644
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 0.989

Least square means for Fiber type

Group	Mean	SEM
P1	12.233	0.620
P2	10.037	0.600

Least square means for Fiber amount

Group	Mean	SEM
0.000	-5.274E-016	1.342
1.500	0.436	1.300
6.250	8.712	1.005
15.000	16.730	0.904
20.000	18.604	0.804
25.000	22.327	0.858

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P1 x 0.000	4.684E-016	1.898
P1 x 1.500	0.873	1.898
P1 x 6.250	14.095	1.450

(Sheet 1 of 4)

Table C8 (Continued)

P1 x 15.000	18.735	1.393	P1 x 20.000	17.169	1.152
P1 x 25.000	22.528	1.123			
P2 x 0.000	-1.523E-015	1.898			
P2 x 1.500	-1.412E-015	1.776			
P2 x 6.250	3.329	1.393			
P2 x 15.000	14.725	1.152			
P2 x 20.000	20.040	1.123			
P2 x 25.000	22.126	1.297			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	Diff of Means	p	q	P<0.05
P1 vs. P2	2.197	2	3.601	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	22.327	6	19.824	Yes
25.000 vs. 1.500	21.891	6	19.883	Yes
25.000 vs. 6.250	13.615	6	14.572	Yes
25.000 vs. 15.000	5.597	6	6.353	Yes
25.000 vs. 20.000	3.723	6	4.477	Yes
20.000 vs. 0.000	18.604	6	16.815	Yes
20.000 vs. 1.500	18.168	6	16.811	Yes
20.000 vs. 6.250	9.892	6	10.867	Yes
20.000 vs. 15.000	1.875	6	2.191	No
15.000 vs. 0.000	16.730	6	14.622	Yes
15.000 vs. 1.500	16.293	6	14.557	Yes
15.000 vs. 6.250	8.018	6	8.388	Yes
6.250 vs. 0.000	8.712	6	7.348	Yes
6.250 vs. 1.500	8.276	6	7.124	Yes
1.500 vs. 0.000	0.436	6	0.330	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	22.528	6	14.446	Yes
25.000 vs. 1.500	21.655	6	13.886	Yes
25.000 vs. 6.250	8.433	6	6.504	Yes
25.000 vs. 20.000	5.359	6	4.710	Yes
25.000 vs. 15.000	3.793	6	2.998	No
15.000 vs. 0.000	18.735	6	11.254	Yes
15.000 vs. 1.500	17.862	6	10.729	Yes
15.000 vs. 6.250	4.640	6	3.264	No
15.000 vs. 20.000	1.565	6	1.225	No
20.000 vs. 0.000	17.169	6	10.936	Yes
20.000 vs. 1.500	16.297	6	10.380	Yes
20.000 vs. 6.250	3.074	6	2.348	No
6.250 vs. 0.000	14.095	6	8.346	Yes
6.250 vs. 1.500	13.222	6	7.829	Yes
1.500 vs. 0.000	0.873	6	0.460	No

(Sheet 2 of 4)

Table C8 (Continued)

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P2**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 0.000	22.126	6	13.612	Yes
25.000 vs. 1.500	22.126	6	14.232	Yes
25.000 vs. 6.250	18.797	6	13.969	Yes
25.000 vs. 15.000	7.401	6	6.034	Yes
25.000 vs. 20.000	2.086	6	1.720	No
20.000 vs. 0.000	20.040	6	12.850	Yes
20.000 vs. 1.500	20.040	6	13.490	Yes
20.000 vs. 6.250	16.710	6	13.209	Yes
20.000 vs. 15.000	5.315	6	4.672	Yes
15.000 vs. 0.000	14.725	6	9.378	Yes
15.000 vs. 1.500	14.725	6	9.839	Yes
15.000 vs. 6.250	11.396	6	8.916	Yes
6.250 vs. 0.000	3.329	6	2.000	No
6.250 vs. 1.500	3.329	6	2.086	No
1.500 vs. 0.000	1.110E-016	6	6.041E-017	No

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 0.029).
The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 6.25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	10.766	2	7.573	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	4.010	2	3.137	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 20 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 20**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	2.870	2	2.523	No

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

(Sheet 3 of 4)

Table C8 (Concluded)

Comparisons for factor: Fiber type within 25 Comparison	Diff of Means	p	q	P<0.05
P1 vs. P2	0.402	2	0.331	No

(Sheet 4 of 4)

Table C9
Two-Way Analysis of Variance, Phase I Modified Data, JCI

Two Way Analysis of Variance — Tuesday, February 17, 1998, 18:20:10

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: JCI

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	380.424	380.424	2.346	0.128
Fiber amount	5	47830.395	9566.079	58.999	<0.001
Fiber type x Fiber amount	5	2622.054	524.411	3.234	0.008
Residual	149	24158.739	162.139		
Total	160	74889.091	468.057		

The difference in the mean values among the different levels of Fiber type is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Fiber amount. There i not a statistically significant difference (p = 0.128).

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significa interaction between Fiber type and Fiber amount. (P = 0.008)

Power of performed test with alpha = 0.0500: for Fiber type : 0.196
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 0.715

Least square means for Fiber type

Group	Mean	SEM
P1	25.855	1.534
P2	22.534	1.533

Least square means for Fiber amount

Group	Mean	SEM
0.000	4.885E-015	3.403
1.500	1.374	3.183
6.250	17.906	2.549
15.000	34.332	2.242
20.000	43.128	2.040
25.000	48.427	2.219

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P1 x 0.000	2.734E-015	4.813
P1 x 1.500	2.748	4.502
P1 x 6.250	26.988	3.676

(Sheet 1 of 4)

Table C9 (Continued)

P1 x 15.000	38.174	3.403	P1 x 20.000	40.707	2.847
P1 x 25.000	46.516	2.847			
P2 x 0.000	7.036E-015	4.813			
P2 x 1.500	6.814E-015	4.502			
P2 x 6.250	8.825	3.532			
P2 x 15.000	30.491	2.921			
P2 x 20.000	45.549	2.921			
P2 x 25.000	50.337	3.403			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	48.427	6	16.858	Yes
25.000 vs. 1.500	47.053	6	17.149	Yes
25.000 vs. 6.250	30.521	6	12.774	Yes
25.000 vs. 15.000	14.094	6	6.319	Yes
25.000 vs. 20.000	5.299	6	2.486	No
20.000 vs. 0.000	43.128	6	15.373	Yes
20.000 vs. 1.500	41.754	6	15.619	Yes
20.000 vs. 6.250	25.222	6	10.927	Yes
20.000 vs. 15.000	8.796	6	4.103	Yes
15.000 vs. 0.000	34.332	6	11.913	Yes
15.000 vs. 1.500	32.959	6	11.970	Yes
15.000 vs. 6.250	16.426	6	6.843	Yes
6.250 vs. 0.000	17.906	6	5.956	Yes
6.250 vs. 1.500	16.532	6	5.733	Yes
1.500 vs. 0.000	1.374	6	0.417	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	46.516	6	11.764	Yes
25.000 vs. 1.500	43.768	6	11.620	Yes
25.000 vs. 6.250	19.528	6	5.940	Yes
25.000 vs. 15.000	8.342	6	2.659	No
25.000 vs. 20.000	5.809	6	2.040	No
20.000 vs. 0.000	40.707	6	10.295	Yes
20.000 vs. 1.500	37.959	6	10.078	Yes
20.000 vs. 6.250	13.719	6	4.173	Yes
20.000 vs. 15.000	2.533	6	0.807	No
15.000 vs. 0.000	38.174	6	9.159	Yes
15.000 vs. 1.500	35.426	6	8.878	Yes
15.000 vs. 6.250	11.186	6	3.158	No
6.250 vs. 0.000	26.988	6	6.302	Yes
6.250 vs. 1.500	24.240	6	5.898	Yes
1.500 vs. 0.000	2.748	6	0.590	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

(Sheet 2 of 4)

Table C9 (Continued)

Comparisons for factor: **Fiber amount within P2Comparison** **Diff of Means** **p** **q**
P<0.05

25.000 vs. 1.500	50.337	6	12.614	Yes
25.000 vs. 0.000	50.337	6	12.077	Yes
25.000 vs. 6.250	41.513	6	11.970	Yes
25.000 vs. 15.000	19.846	6	6.258	Yes
25.000 vs. 20.000	4.788	6	1.510	No
20.000 vs. 1.500	45.549	6	12.003	Yes
20.000 vs. 0.000	45.549	6	11.442	Yes
20.000 vs. 6.250	36.724	6	11.332	Yes
20.000 vs. 15.000	15.058	6	5.155	Yes
15.000 vs. 1.500	30.491	6	8.035	Yes
15.000 vs. 0.000	30.491	6	7.659	Yes
15.000 vs. 6.250	21.666	6	6.685	Yes
6.250 vs. 1.500	8.825	6	2.181	No
6.250 vs. 0.000	8.825	6	2.091	No
0.000 vs. 1.500	2.220E-016	6	4.765E-017	No

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is greater than would be expected by chance. There is a statistically significant difference (P = 0.004).

Comparisons for factor: **Fiber type within 1.5**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	2.747	2	0.610	No

The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 6.25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	18.163	2	5.039	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	7.683	2	2.422	No

The difference in the mean values among the different levels of Fiber type evaluated within level 20 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 20**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	4.842	2	1.679	No

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

(Sheet 3 of 4)

Table C9 (Concluded)

Comparisons for factor: **Fiber type within 25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	3.821	2	1.218	No

(Sheet 4 of 4)

Table C10
Two-Way Analysis of Variance, Phase I, Modified Data, EAR

Two Way Analysis of Variance Tuesday, February 17, 1998, 18:30:20

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: EAR

Normality Test: Failed (P = <0.001)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	0.0139	0.0139	0.495	0.483
Fiber amount	5	13.804	2.761	98.481	<0.001
Fiber type x Fiber amount	5	0.906	0.181	6.464	<0.001
Residual	149	4.177	0.0280		
Total	160	18.860	0.118		

The difference in the mean values among the different levels of Fiber type is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Fiber amount. There is not a statistically significant difference (p = 0.483).

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 0.0500
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 0.993

Least square means for Fiber type

Group	Mean	SEM
P1	0.421	0.0203
P2	0.401	0.0201

Least square means for Fiber amount

Group	Mean	SEM
0.000	5.551E-017	0.0447
1.500	0.0306	0.0419
6.250	0.296	0.0335
15.000	0.589	0.0301
20.000	0.719	0.0265
25.000	0.832	0.0292

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P1 x 0.000	3.903E-017	0.0633
P1 x 1.500	0.0613	0.0592
P1 x 6.250	0.433	0.0483

(Sheet 1 of 4)

Table C10 (Continued)

P1 x 15.000	0.620	0.0464	P1 x 20.000	0.629	0.0374
P1 x 25.000	0.785	0.0374			
P2 x 0.000	7.199E-017	0.0633			
P2 x 1.500	5.464E-017	0.0592			
P2 x 6.250	0.160	0.0464			
P2 x 15.000	0.558	0.0384			
P2 x 20.000	0.809	0.0374			
P2 x 25.000	0.879	0.0447			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	0.832	6	22.031	Yes
25.000 vs. 1.500	0.802	6	22.217	Yes
25.000 vs. 6.250	0.536	6	17.057	Yes
25.000 vs. 15.000	0.243	6	8.192	Yes
25.000 vs. 20.000	0.113	6	4.071	Yes
20.000 vs. 0.000	0.719	6	19.550	Yes
20.000 vs. 1.500	0.688	6	19.649	Yes
20.000 vs. 6.250	0.423	6	13.990	Yes
20.000 vs. 15.000	0.130	6	4.567	Yes
15.000 vs. 0.000	0.589	6	15.446	Yes
15.000 vs. 1.500	0.559	6	15.316	Yes
15.000 vs. 6.250	0.293	6	9.193	Yes
6.250 vs. 0.000	0.296	6	7.494	Yes
6.250 vs. 1.500	0.266	6	7.006	Yes
1.500 vs. 0.000	0.0306	6	0.707	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	0.785	6	15.098	Yes
25.000 vs. 1.500	0.724	6	14.613	Yes
25.000 vs. 6.250	0.352	6	8.154	Yes
25.000 vs. 15.000	0.165	6	3.912	No
25.000 vs. 20.000	0.156	6	4.180	Yes
20.000 vs. 0.000	0.629	6	12.088	Yes
20.000 vs. 1.500	0.567	6	11.453	Yes
20.000 vs. 6.250	0.196	6	4.534	Yes
20.000 vs. 15.000	0.00850	6	0.202	No
15.000 vs. 0.000	0.620	6	11.171	Yes
15.000 vs. 1.500	0.559	6	10.503	Yes
15.000 vs. 6.250	0.187	6	3.956	No
6.250 vs. 0.000	0.433	6	7.681	Yes
6.250 vs. 1.500	0.371	6	6.870	Yes
1.500 vs. 0.000	0.0612	6	1.000	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

(Sheet 2 of 4)

Table C10 (Continued)

Comparisons for factor: **Fiber amount within P2**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 1.500	0.879	6	16.757	Yes
25.000 vs. 0.000	0.879	6	16.044	Yes
25.000 vs. 6.250	0.719	6	15.774	Yes
25.000 vs. 15.000	0.321	6	7.695	Yes
25.000 vs. 20.000	0.0703	6	1.704	No
20.000 vs. 1.500	0.809	6	16.334	Yes
20.000 vs. 0.000	0.809	6	15.560	Yes
20.000 vs. 6.250	0.649	6	15.387	Yes
20.000 vs. 15.000	0.251	6	6.607	Yes
15.000 vs. 1.500	0.558	6	11.191	Yes
15.000 vs. 0.000	0.558	6	10.668	Yes
15.000 vs. 6.250	0.398	6	9.350	Yes
6.250 vs. 1.500	0.160	6	3.007	No
6.250 vs. 0.000	0.160	6	2.883	No
0.000 vs. 1.500	1.735E-017	6	2.831E-016	No

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 1.5**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	0.0612	2	1.035	No

The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 6.25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	0.272	2	5.750	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P1 vs. P2	0.0616	2	1.445	No

The difference in the mean values among the different levels of Fiber type evaluated within level 20 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 20**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	0.180	2	4.821	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

(Sheet 3 of 4)

Table C10 (Concluded)

Comparisons for factor: **Fiber type within 25**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	0.0943	2	2.285	No

(Sheet 4 of 4)

Table C11
Two-Way Analysis of Variance, Phase II, Modified Data, I30

Two Way Analysis of Variance Tuesday, February 17, 1998, 18:48:38

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: I30

Normality Test: Failed (P = <0.001)

Equal Variance Test: Passed (P = 0.385)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	119.224	119.224	24.900	<0.001
Fiber amount	4	4885.242	1221.310	255.070	<0.001
Fiber type x Fiber amount	4	470.920	117.730	24.588	<0.001
Residual	58	277.712	4.788		
Total	67	6194.099	92.449		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 0.999
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 1.000

Least square means for Fiber type

Group	Mean	SEM
P2	7.182	0.442
P1	3.892	0.489

Least square means for Fiber amount

Group	Mean	SEM
0.000	-8.040E-016	0.547
1.500	-2.534E-015	1.094
6.250	-2.657E-015	0.774
15.000	7.200	0.616
25.000	20.485	0.492

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P2 x 0.000	2.612E-015	0.774
P2 x 1.500	-5.182E-015	1.547
P2 x 6.250	-1.784E-016	1.094

(Sheet 1 of 3)

Table C11 (Continued)

P2 x 15.000	14.400	0.565	P2 x 25.000	21.508	0.607
P1 x 0.000	-4.220E-015	0.774			
P1 x 1.500	1.129E-016	1.547			
P1 x 6.250	-5.135E-015	1.094			
P1 x 15.000	-2.193E-015	1.094			
P1 x 25.000	19.462	0.774			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	3.289	2	7.057	Yes

Comparisons for factor: **Fiber amount**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 6.250	20.485	5	31.606	Yes
25.000 vs. 1.500	20.485	5	24.153	Yes
25.000 vs. 0.000	20.485	5	39.389	Yes
25.000 vs. 15.000	13.285	5	23.847	Yes
15.000 vs. 6.250	7.200	5	10.298	Yes
15.000 vs. 1.500	7.200	5	8.111	Yes
15.000 vs. 0.000	7.200	5	12.363	Yes
0.000 vs. 6.250	1.853E-015	5	2.765E-015	No
0.000 vs. 1.500	1.730E-015	5	2.001E-015	No
1.500 vs. 6.250	1.223E-016	5	1.291E-016	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P2**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 1.500	21.508	5	18.301	Yes
25.000 vs. 6.250	21.508	5	24.312	Yes
25.000 vs. 0.000	21.508	5	30.935	Yes
25.000 vs. 15.000	7.108	5	12.124	Yes
15.000 vs. 1.500	14.400	5	12.363	Yes
15.000 vs. 6.250	14.400	5	16.538	Yes
15.000 vs. 0.000	14.400	5	21.258	Yes
0.000 vs. 1.500	7.794E-015	5	6.372E-015	No
0.000 vs. 6.250	2.791E-015	5	2.945E-015	No
6.250 vs. 1.500	5.003E-015	5	3.734E-015	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 6.250	19.463	5	20.541	Yes
25.000 vs. 0.000	19.463	5	25.157	Yes
25.000 vs. 15.000	19.463	5	20.541	Yes
25.000 vs. 1.500	19.462	5	15.911	Yes
1.500 vs. 6.250	5.248E-015	5	3.916E-015	No

(Sheet 2 of 3)

Table C11 (Concluded)

1.500 vs. 0.000	4.333E-015	5	3.542E-015	No	1.500 vs. 15.000 2.306E-015
1.721E-015	No				
15.000 vs. 6.250	2.942E-015	5	2.689E-015	No	
15.000 vs. 0.000	2.028E-015	5	2.140E-015	No	
0.000 vs. 6.250	9.146E-016	5	9.653E-016	No	

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	14.400	2	16.538	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	2.046	2	2.943	Yes

(Sheet 3 of 3)

Table C12
Two-Way Analysis of Variance, Phase II, Modified Data, I50

Two Way Analysis of Variance Tuesday, February 17, 1998, 18:51:22

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: I50

Normality Test: Failed (P = <0.001)

Equal Variance Test: Passed (P = 0.436)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	297.690	297.690	36.493	<0.001
Fiber amount	4	12006.168	3001.542	367.951	<0.001
Fiber type x Fiber amount	4	1195.139	298.785	36.627	<0.001
Residual	55	448.660	8.157		
Total	64	15107.479	236.054		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 1.000

Least square means for Fiber type

Group	Mean	SEM
P2	11.634	0.580
P1	6.400	0.643

Least square means for Fiber amount

Group	Mean	SEM
0.000	-1.013E-015	0.714
1.500	-4.803E-015	1.428
6.250	-2.177E-015	1.010
15.000	11.486	0.804
25.000	33.600	0.690

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P2 x 0.000	2.010E-015	1.010
P2 x 1.500	-8.494E-015	2.020
P2 x 6.250	-1.843E-015	1.428

(Sheet 1 of 3)

Table C12 (Continued)

P2 x 15.000	22.971	0.737	P2 x 25.000	35.199	0.861
P1 x 0.000	-4.036E-015	1.010			
P1 x 1.500	-1.113E-015	2.020			
P1 x 6.250	-2.511E-015	1.428			
P1 x 15.000	-6.106E-015	1.428			
P1 x 25.000	32.001	1.080			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	5.234	2	8.543	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 1.500	33.600	5	29.957	Yes
25.000 vs. 6.250	33.600	5	38.845	Yes
25.000 vs. 0.000	33.600	5	47.840	Yes
25.000 vs. 15.000	22.115	5	29.519	Yes
15.000 vs. 1.500	11.486	5	9.913	Yes
15.000 vs. 6.250	11.486	5	12.586	Yes
15.000 vs. 0.000	11.486	5	15.110	Yes
0.000 vs. 1.500	3.790E-015	5	3.357E-015	No
0.000 vs. 6.250	1.164E-015	5	1.331E-015	No
6.250 vs. 1.500	2.626E-015	5	2.124E-015	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P2**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 1.500	35.199	5	22.673	Yes
25.000 vs. 6.250	35.199	5	29.850	Yes
25.000 vs. 0.000	35.199	5	37.509	Yes
25.000 vs. 15.000	12.228	5	15.252	Yes
15.000 vs. 1.500	22.971	5	15.110	Yes
15.000 vs. 6.250	22.971	5	20.213	Yes
15.000 vs. 0.000	22.971	5	25.981	Yes
0.000 vs. 1.500	1.050E-014	5	6.579E-015	No
0.000 vs. 6.250	3.853E-015	5	3.116E-015	No
6.250 vs. 1.500	6.651E-015	5	3.803E-015	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 15.000	32.001	5	25.281	Yes
25.000 vs. 0.000	32.001	5	30.616	Yes
25.000 vs. 6.250	32.001	5	25.281	Yes
25.000 vs. 1.500	32.001	5	19.763	Yes
1.500 vs. 15.000	4.993E-015	5	2.855E-015	No

(Sheet 2 of 3)

Table C12 (Concluded)

1.500 vs. 0.000	2.923E-015	5	1.831E-015	No	1.500 vs. 6.250	1.398E-015
7.993E-016	No					
6.250 vs. 15.000	3.595E-015	5	2.518E-015	No		
6.250 vs. 0.000	1.525E-015	5	1.233E-015	No		
0.000 vs. 15.000	2.070E-015	5	1.674E-015	No		

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	22.971	2	20.213	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	3.198	2	3.275	Yes

(Sheet 3 of 3)

Table C13
Two-Way Analysis of Variance, Phase II, Modified Data, JCI

Two Way Analysis of Variance Tuesday, February 17, 1998, 18:54:14

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: JCI

Normality Test: Failed (P = <0.001)

Equal Variance Test: Passed (P = 0.554)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	1544.368	1544.368	47.763	<0.001
Fiber amount	4	56540.461	14135.115	437.160	<0.001
Fiber type x Fiber amount	4	5239.508	1309.877	40.511	<0.001
Residual	56	1810.702	32.334		
Total	65	70157.467	1079.346		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 1.000

Least square means for Fiber type

Group	Mean	SEM
P2	24.902	1.154
P1	13.035	1.271

Least square means for Fiber amount

Group	Mean	SEM
0.000	-1.429E-015	1.422
1.500	-5.610E-015	2.843
6.250	-8.948E-015	2.010
15.000	24.490	1.612
25.000	70.352	1.298

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P2 x 0.000	2.317E-015	2.010
P2 x 1.500	-4.371E-015	4.021
P2 x 6.250	7.633E-015	2.843

(Sheet 1 of 3)

Table C13 (Continued)

P2 x 15.000	48.980	1.520	P2 x 25.000	75.530	1.641
P1 x 0.000	-5.177E-015	2.010			
P1 x 1.500	-6.848E-015	4.021			
P1 x 6.250	-2.553E-014	2.843			
P1 x 15.000	-1.860E-015	2.843			
P1 x 25.000	65.174	2.010			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	11.867	2	9.774	Yes

Comparisons for factor: **Fiber amount**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 6.250	70.352	5	41.579	Yes
25.000 vs. 1.500	70.352	5	31.834	Yes
25.000 vs. 0.000	70.352	5	51.689	Yes
25.000 vs. 15.000	45.862	5	31.342	Yes
15.000 vs. 6.250	24.490	5	13.441	Yes
15.000 vs. 1.500	24.490	5	10.597	Yes
15.000 vs. 0.000	24.490	5	16.115	Yes
0.000 vs. 6.250	7.518E-015	5	4.318E-015	No
0.000 vs. 1.500	4.181E-015	5	1.860E-015	No
1.500 vs. 6.250	3.338E-015	5	1.356E-015	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P2**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 1.500	75.530	5	24.595	Yes
25.000 vs. 0.000	75.530	5	41.155	Yes
25.000 vs. 6.250	75.530	5	32.536	Yes
25.000 vs. 15.000	26.550	5	16.785	Yes
15.000 vs. 1.500	48.980	5	16.115	Yes
15.000 vs. 0.000	48.980	5	27.485	Yes
15.000 vs. 6.250	48.980	5	21.486	Yes
6.250 vs. 1.500	1.200E-014	5	3.447E-015	No
6.250 vs. 0.000	5.316E-015	5	2.159E-015	No
0.000 vs. 1.500	6.688E-015	5	2.104E-015	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
25.000 vs. 6.250	65.174	5	26.469	Yes
25.000 vs. 1.500	65.174	5	20.503	Yes
25.000 vs. 0.000	65.174	5	32.418	Yes
25.000 vs. 15.000	65.174	5	26.469	Yes
15.000 vs. 6.250	2.367E-014	5	8.325E-015	No

(Sheet 2 of 3)

Table C13 (Concluded)

15.000 vs. 1.500	4.989E-015	5	1.433E-015	No	15.000 vs. 0.000 3.317E-0
1.347E-015	No				
0.000 vs. 6.250	2.035E-014	5	8.266E-015	No	
0.000 vs. 1.500	1.671E-015	5	5.258E-016	No	
1.500 vs. 6.250	1.868E-014	5	5.365E-015	No	

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	48.980	2	21.486	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 25**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
P2 vs. P1	10.356	2	5.643	Yes

(Sheet 3 of 3)

Table C14
Two-Way Analysis of Variance, Phase II, Modified Data, EAR

Two Way Analysis of Variance — Tuesday, February 17, 1998, 18:56:40

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: EAR

Normality Test: Failed (P = <0.001)

Equal Variance Test: Passed (P = 0.184)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	0.720	0.720	29.200	<0.001
Fiber amount	4	23.316	5.829	236.311	<0.001
Fiber type x Fiber amount	4	2.084	0.521	21.125	<0.001
Residual	58	1.431	0.0247		
Total	67	30.459	0.455		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Fiber type depends on what level of Fiber amount is present. There is a statistically significant interaction between Fiber type and Fiber amount. (P = <0.001)

Power of performed test with alpha = 0.0500: for Fiber type : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000
Power of performed test with alpha = 0.0500: for Fiber type x Fiber amount : 1.000

Least square means for Fiber type

Group	Mean	SEM
P2	0.509	0.0317
P1	0.253	0.0351

Least square means for Fiber amount

Group	Mean	SEM
0.000	1.138E-018	0.0393
1.500	1.198E-016	0.0785
6.250	-3.762E-017	0.0555
15.000	0.489	0.0442
25.000	1.415	0.0353

Least square means for Fiber type x Fiber amount

Group	Mean	SEM
P2 x 0.000	2.004E-016	0.0555
P2 x 1.500	-1.966E-016	0.111
P2 x 6.250	6.381E-017	0.0785

(Sheet 1 of 3)

Table C14 (Continued)

P2 x 15.000	0.979	0.0406	P2 x 25.000	1.565	0.0436
P1 x 0.000	-1.981E-016	0.0555			
P1 x 1.500	4.361E-016	0.111			
P1 x 6.250	-1.390E-016	0.0785			
P1 x 15.000	3.296E-017	0.0785			
P1 x 25.000	1.265	0.0555			

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	0.256	2	7.642	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 6.250	1.415	5	30.412	Yes
25.000 vs. 0.000	1.415	5	37.901	Yes
25.000 vs. 1.500	1.415	5	23.240	Yes
25.000 vs. 15.000	0.925	5	23.144	Yes
15.000 vs. 6.250	0.489	5	9.751	Yes
15.000 vs. 0.000	0.489	5	11.706	Yes
15.000 vs. 1.500	0.489	5	7.680	Yes
1.500 vs. 6.250	1.574E-016	5	2.314E-015	No
1.500 vs. 0.000	1.186E-016	5	1.911E-015	No
0.000 vs. 6.250	3.876E-017	5	8.060E-016	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P2 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P2**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 1.500	1.565	5	18.548	Yes
25.000 vs. 6.250	1.565	5	24.640	Yes
25.000 vs. 0.000	1.565	5	31.352	Yes
25.000 vs. 15.000	0.586	5	13.924	Yes
15.000 vs. 1.500	0.979	5	11.706	Yes
15.000 vs. 6.250	0.979	5	15.660	Yes
15.000 vs. 0.000	0.979	5	20.129	Yes
0.000 vs. 1.500	3.970E-016	5	4.522E-015	No
0.000 vs. 6.250	1.366E-016	5	2.009E-015	No
6.250 vs. 1.500	2.604E-016	5	2.707E-015	No

The difference in the mean values among the different levels of Fiber amount evaluated within level P1 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber amount within P1**

Comparison	Diff of Means	p	q	P<0.05
25.000 vs. 0.000	1.265	5	22.781	Yes
25.000 vs. 6.250	1.265	5	18.601	Yes
25.000 vs. 15.000	1.265	5	18.601	Yes
25.000 vs. 1.500	1.265	5	14.408	Yes
1.500 vs. 0.000	6.342E-016	5	7.223E-015	No

(Sheet 2 of 3)

Table C14 (Concluded)

1.500 vs. 6.250	5.751E-016	5	5.980E-015	No		
1.500 vs. 15.000	4.031E-016	5	4.191E-015	No		
15.000 vs. 0.000	2.311E-016	5	3.398E-015	No		
15.000 vs. 6.250	1.720E-016	5	2.190E-015	No		
6.250 vs. 0.000	5.909E-017	5	8.689E-016	No		

The difference in the mean values among the different levels of Fiber type evaluated within level 0 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 1.5 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 6.25 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 1.000).
The difference in the mean values among the different levels of Fiber type evaluated within level 15 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 15**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	0.979	2	15.660	Yes

The difference in the mean values among the different levels of Fiber type evaluated within level 25 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **Fiber type within 25**

Comparison	Diff of Means	p	q	P<0.05
P2 vs. P1	0.300	2	6.004	Yes

(Sheet 3 of 3)

Table C15
Two-Way Analysis of Variance, Phase I Versus Phase II, Modified Data, I30

Two Way Analysis of Variance Thursday, March 26, 1998, 12:14:23

Data source: Data 1 in Notebook

General Linear Model (No Interactions)

Dependent Variable: I30

Normality Test: Passed (P = 0.068)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Phase #	1	542.064	542.064	84.697	<0.001
Fiber amount	5	4630.539	926.108	144.703	<0.001
Residual	117	748.808	6.400		
Total	123	6428.899	52.267		

The difference in the mean values among the different levels of Phase # is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Phase #. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.0500: for Phase # : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000

Least square means for Phase #

Group	Mean	SEM
I	5.823	0.283
II	11.153	0.504

Least square means for Fiber amount

Group	Mean	SEM
15.000	11.686	0.435
20.000	14.816	0.636
25.000	17.370	0.479
0.000	-0.178	0.653
1.500	2.665	0.851
6.250	4.570	0.678

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Phase #**

Comparison	Diff of Means	p	q	P<0.05
II vs. I	5.330	2	13.038	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05

(Continued)

Table C15 (Concluded)

25.000 vs. 0.000	17.547	6	30.638	Yes
25.000 vs. 1.500	14.705	6	21.304	Yes
25.000 vs. 6.250	12.800	6	21.802	Yes
25.000 vs. 15.000	5.684	6	12.427	Yes
25.000 vs. 20.000	2.554	6	4.540	Yes
20.000 vs. 0.000	14.994	6	23.262	Yes
20.000 vs. 1.500	12.151	6	16.182	Yes
20.000 vs. 6.250	10.246	6	15.587	Yes
20.000 vs. 15.000	3.130	6	5.748	Yes
15.000 vs. 0.000	11.863	6	21.368	Yes
15.000 vs. 1.500	9.021	6	13.349	Yes
15.000 vs. 6.250	7.116	6	12.485	Yes
6.250 vs. 0.000	4.747	6	7.127	Yes
6.250 vs. 1.500	1.905	6	2.475	No
1.500 vs. 0.000	2.843	6	3.747	No

Table C16
Two-Way Analysis of Variance, Phase I Versus Phase II, Modified Data, I50

Two Way Analysis of Variance Thursday, March 26, 1998, 12:38:52

Data source: Data 1 in Notebook

General Linear Model (No Interactions)

Dependent Variable: I50

Normality Test: Failed (P = 0.031)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Fiber type	1	1252.924	1252.924	84.804	<0.001
Fiber amount	5	12332.282	2466.456	166.941	<0.001
Residual	115	1699.055	14.774		
Total	121	16256.543	134.352		

The difference in the mean values among the different levels of Fiber type is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Fiber type. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.0500: for Fiber type : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000

Least square means for Fiber type

Group	Mean	SEM
I	9.515	0.429
II	17.753	0.782

Least square means for Fiber amount

Group	Mean	SEM
15.000	18.848	0.661
20.000	24.159	0.969
25.000	28.291	0.757
0.000	-0.275	0.993
1.500	4.119	1.295
6.250	6.665	1.034

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Fiber type**

Comparison	Diff of Means	p	q	P<0.05
II vs. I	8.238	2	13.057	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05

(Continued)

Table C16 (Concluded)

25.000 vs. 0.000	28.565	6	32.356	Yes
25.000 vs. 1.500	24.172	6	22.787	Yes
25.000 vs. 6.250	21.626	6	23.866	Yes
25.000 vs. 15.000	9.443	6	13.286	Yes
25.000 vs. 20.000	4.132	6	4.753	Yes
20.000 vs. 0.000	24.433	6	24.907	Yes
20.000 vs. 1.500	20.040	6	17.521	Yes
20.000 vs. 6.250	17.494	6	17.459	Yes
20.000 vs. 15.000	5.311	6	6.403	Yes
15.000 vs. 0.000	19.122	6	22.669	Yes
15.000 vs. 1.500	14.729	6	14.323	Yes
15.000 vs. 6.250	12.183	6	14.037	Yes
6.250 vs. 0.000	6.940	6	6.846	Yes
6.250 vs. 1.500	2.546	6	2.172	No
1.500 vs. 0.000	4.394	6	3.807	No

Table C17
Two-Way Analysis of Variance, Phase I Versus Phase II, Modified Data, JCI

Two Way Analysis of Variance Thursday, March 26, 1998, 12:48:43

Data source: Data 1 in Notebook

General Linear Model (No Interactions)

Dependent Variable: JCI

Normality Test: Passed (P = 0.153)

Equal Variance Test: Failed (P = 0.023)

Source of Variation	DF	SS	MS	F	P
Phase #	1	5326.055	5326.055	85.372	<0.001
Fiber amount	5	59682.893	11936.579	191.332	<0.001
Residual	113	7049.695	62.387		
Total	119	76970.657	646.812		

The difference in the mean values among the different levels of Phase # is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Phase #. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.0500: for Phase # : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000

Least square means for Phase #

Group	Mean	SEM
I	21.393	0.890
II	38.474	1.610

Least square means for Fiber amount

Group	Mean	SEM
15.000	39.629	1.382
20.000	54.089	2.034
25.000	62.622	1.551
0.000	-0.569	2.040
1.500	8.540	2.663
6.250	15.289	2.127

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Phase #**

Comparison	Diff of Means	p	q	P<0.05
II vs. I	17.081	2	13.128	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05

(Continued)

Table C17 (Concluded)

25.000 vs. 0.000	63.191	6	34.872	Yes
25.000 vs. 1.500	54.081	6	24.817	Yes
25.000 vs. 6.250	47.333	6	25.430	Yes
25.000 vs. 15.000	22.993	6	15.654	Yes
25.000 vs. 20.000	8.532	6	4.717	Yes
20.000 vs. 0.000	54.659	6	26.830	Yes
20.000 vs. 1.500	45.549	6	19.221	Yes
20.000 vs. 6.250	38.801	6	18.644	Yes
20.000 vs. 15.000	14.460	6	8.316	Yes
15.000 vs. 0.000	40.198	6	23.068	Yes
15.000 vs. 1.500	31.088	6	14.653	Yes
15.000 vs. 6.250	24.340	6	13.570	Yes
6.250 vs. 0.000	15.858	6	7.609	Yes
6.250 vs. 1.500	6.748	6	2.800	No
1.500 vs. 0.000	9.110	6	3.840	No

Table C18
Two-Way Analysis of Variance, Phase I Versus Phase II, Modified Data, EAR

Two Way Analysis of Variance Thursday, March 26, 1998, 12:54:50

Data source: Data 1 in Notebook

General Linear Model (No Interactions)

Dependent Variable: EAR

Normality Test: Failed (P = 0.044)

Equal Variance Test: Failed (P = <0.001)

Source of Variation	DF	SS	MS	F	P
Phase #	1	3.424	3.424	95.945	<0.001
Fiber amount	5	21.588	4.318	120.988	<0.001
Residual	114	4.068	0.0357		
Total	120	32.001	0.267		

The difference in the mean values among the different levels of Phase # is greater than would be expected by chance after allowing for effects of differences in Fiber amount. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Fiber amount is greater than would be expected by chance after allowing for effects of differences in Phase #. There is a statistically significant difference (p = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.0500: for Phase # : 1.000
Power of performed test with alpha = 0.0500: for Fiber amount : 1.000

Least square means for Phase #

Group	Mean	SEM
I	0.376	0.0214
II	0.807	0.0379

Least square means for Fiber amount

Group	Mean	SEM
15.000	0.770	0.0334
20.000	1.024	0.0476
25.000	1.217	0.0364
0.000	-0.0144	0.0488
1.500	0.215	0.0637
6.250	0.338	0.0508

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Phase #**

Comparison	Diff of Means	p	q	P<0.05
II vs. I	0.431	2	13.993	Yes

Comparisons for factor: **Fiber amount**

Comparison	Diff of Means	p	q	P<0.05

(Continued)

Table C18 (Concluded)

25.000 vs. 0.000	1.232	6	28.620	Yes
25.000 vs. 1.500	1.002	6	19.325	Yes
25.000 vs. 6.250	0.879	6	19.902	Yes
25.000 vs. 15.000	0.447	6	12.796	Yes
25.000 vs. 20.000	0.193	6	4.550	Yes
20.000 vs. 0.000	1.039	6	21.545	Yes
20.000 vs. 1.500	0.809	6	14.391	Yes
20.000 vs. 6.250	0.687	6	13.942	Yes
20.000 vs. 15.000	0.254	6	6.176	Yes
15.000 vs. 0.000	0.785	6	18.762	Yes
15.000 vs. 1.500	0.555	6	10.915	Yes
15.000 vs. 6.250	0.433	6	10.057	Yes
6.250 vs. 0.000	0.352	6	7.068	Yes
6.250 vs. 1.500	0.122	6	2.124	No
1.500 vs. 0.000	0.230	6	4.052	No

Table C19
Two-Way Analysis of Variance, Chloride Permeability, 28-days Age

Two Way Analysis of Variance Thursday, April 09, 1998, 11:56:52

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: 28day cl

Normality Test: Passed (P = 0.329)

Equal Variance Test: Passed (P = 0.851)

Source of Variation	DF	SS	MS	F	P
fiber vol	1	6965188.231	6965188.231	14.499	0.001
w/c	1	4307608.898	4307608.898	8.967	0.008
fiber vol x w/c	1	5790278.231	5790278.231	12.053	0.003
Residual	18	8647099.583	480394.421		
Total	21	26940930.364	1282901.446		

The difference in the mean values among the different levels of fiber vol is greater than would be expected by chance after allowing for effects of differences in w/c. There is a statistically significant difference (p = 0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of w/c is greater than would be expected by chance after allowing for effects of differences in fiber vol. There is a statistically significant difference (p = 0.008). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of fiber vol depends on what level of w/c is present. There is a statistically significant interaction between fiber vol and w/c. (P = 0.003)

Power of performed test with alpha = 0.0500: for fiber vol : 0.949
Power of performed test with alpha = 0.0500: for w/c : 0.771
Power of performed test with alpha = 0.0500: for fiber vol x w/c : 0.897

Least square means for fiber vol

Group	Mean	SEM
1.640	5753.125	223.699
0.000	4610.333	200.082

Least square means for w/c

Group	Mean	SEM
0.480	5631.083	200.082
0.400	4732.375	223.699

Least square means for fiber vol x w/c

Group	Mean	SEM
1.640 x 0.480	5681.500	282.959
1.640 x 0.400	5824.750	346.552
0.000 x 0.480	5580.667	282.959
0.000 x 0.400	3640.000	282.959

All Pairwise Multiple Comparison Procedures (Tukey Test):

(Sheet 1 of 3)

Table C19 (Continued)

Comparisons for factor: **fiber volComparison** **Diff of Means** **p** **q** **P<0.05**

1.640 vs. 0.000	1142.792	2	5.385	Yes

Comparisons for factor: **w/c**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
0.480 vs. 0.400	898.708	2	4.235	Yes

The difference in the mean values among the different levels of w/c evaluated within level 1.64 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 0.171).
The difference in the mean values among the different levels of w/c evaluated within level 0 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **w/c within 0**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
0.480 vs. 0.400	1940.667	2	6.858	Yes

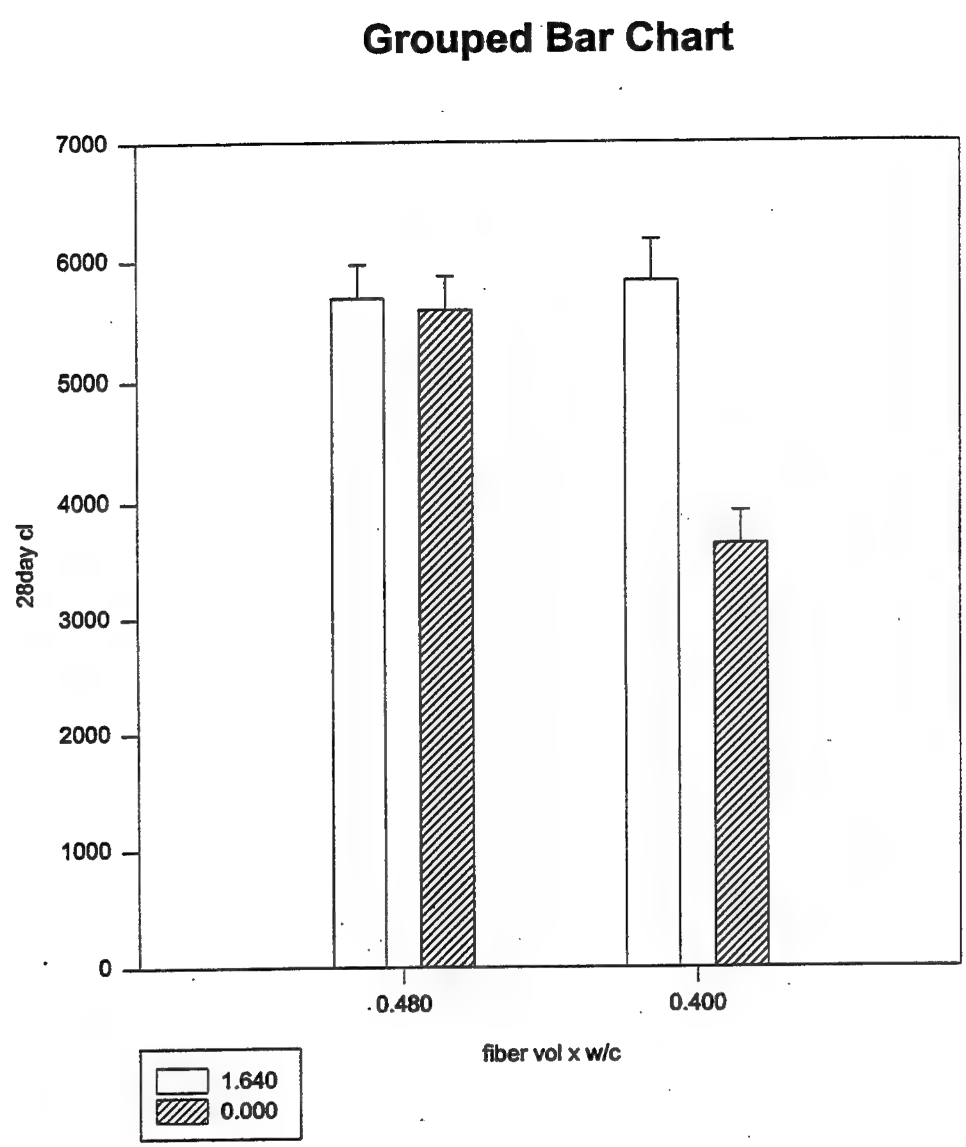
The difference in the mean values among the different levels of fiber vol evaluated within level 0.48 is not great enough to exclude the possibility that the difference is just due to random sampling variability. There is not a statistically significant difference (P = 0.176).
The difference in the mean values among the different levels of fiber vol evaluated within level 0.4 is greater than would be expected by chance. There is a statistically significant difference (P = <0.001).

Comparisons for factor: **fiber vol within 0.4**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
1.640 vs. 0.000	2184.750	2	6.906	Yes

(Sheet 2 of 3)

Table C19 (Concluded)



(Sheet 3 of 3)

Table C20
Two-Way Analysis of Variance, Chloride Permeability, 90-days Age

Two Way Analysis of Variance Thursday, April 09, 1998, 15:00:20

Data source: Data 1 in Notebook

General Linear Model

Dependent Variable: 90day cl

Normality Test: Failed (P = 0.022)

Equal Variance Test: Passed (P = 0.437)

Source of Variation	DF	SS	MS	F	P
fiber vol	1	3137470.701	3137470.701	10.563	0.005
w/c	1	481747.571	481747.571	1.622	0.220
fiber vol x w/c	1	858038.006	858038.006	2.889	0.107
Residual	17	5049492.533	297028.973		
Total	20	9448293.238	472414.662		

The difference in the mean values among the different levels of fiber vol is greater than would be expected by chance after allowing for effects of differences in w/c. There is a statistically significant difference (p = 0.005). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of w/c is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in fiber vol. There is not a statistically significant difference (p = 0.220).

The effect of different levels of fiber vol does not depend on what level of w/c is present. There is not a statistically significant interaction between fiber vol and w/c. (P = 0.107)

Power of performed test with alpha = 0.0500: for fiber vol : 0.844
Power of performed test with alpha = 0.0500: for w/c : 0.109
Power of performed test with alpha = 0.0500: for fiber vol x w/c : 0.241

Least square means for fiber vol

Group	Mean	SEM
1.640	3288.167	165.008
0.000	2512.700	172.345

Least square means for w/c

Group	Mean	SEM
0.480	3052.367	165.008
0.400	2748.500	172.345

Least square means for fiber vol x w/c

Group	Mean	SEM
1.640 x 0.480	3237.333	222.497
1.640 x 0.400	3339.000	243.733
0.000 x 0.480	2867.400	243.733
0.000 x 0.400	2158.000	243.733

All Pairwise Multiple Comparison Procedures (Tukey Test):

(Sheet 1 of 3)

Table C20 (Continued)

Comparisons for factor: **fiber volComparison** **Diff of Means** **p** **q** **P<0.05**

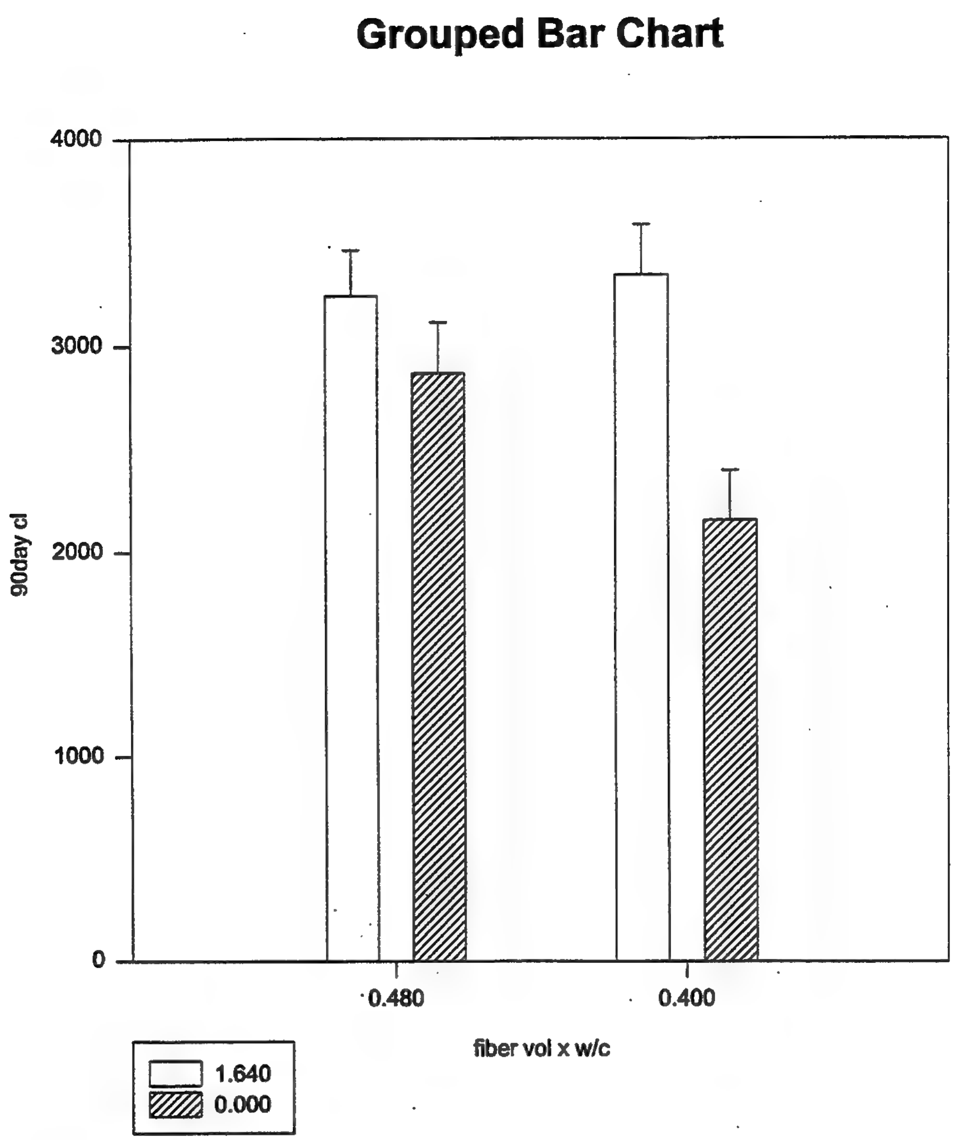
1.640 vs. 0.000	775.467	2	4.596	Yes

Comparisons for factor: **w/c**

Comparison	**Diff of Means**	**p**	**q**	**P<0.05**
0.480 vs. 0.400	303.867	2	1.801	No

(Sheet 2 of 3)

Table C20 (Concluded)



(Sheet 3 of 3)

Appendix D
3M Technical Literature and Case Histories

3M

Polyolefin Fibers

Product Data

1. Product Description

The 3M™ polyolefin fiber system consists of polymeric fibers and a fiber delivery system. 3M fibers combine the structural benefits of steel fibers with the material benefits of polyolefin.

3M fibers allow high volume loading (typical 1.6%, maximum 3%) and rapid uniform dispersion with no fiber balling. 3M fibers allow higher fiber volume content than existing synthetic and steel fibers without loss of rheological properties needed for proper mixing and placement. This is important because fiber content has been shown to directly affect the ability to increase concrete material performance characteristics.

Unlike many fibrillated or small diameter monofilament synthetic fibers, 3M fibers will not hang-up on rebar or other obstructions during concrete placement.

Basic Use: 3M fibers are used as secondary reinforcement in cast-in-place concrete, precast concrete and wet mix shotcrete applications. Because 3M fibers can be added to concrete at higher loading rates than other synthetic fibers, they enhance concrete material performance properties, such as toughness, flexural strength, impact strength and fatigue endurance, as steel fibers do. Like all fibers, 3M fibers help control thermal cracking in addition to plastic and drying shrinkage cracking.

3M fibers are an alternative to welded wire fabric (WWF) in slab on grade and other non-structural applications because 3M fibers provide three dimensional reinforcement, assured positioning and reduced installation labor from WWF.

3M Fibers Combine Structural Advantages of Steel and Material Advantages of Polyolefin

Property/Benefits	3M Fibers 1.6% by volume (14.5 kg/cu. m, 25 lbs./cu. yd.)	Steel Fiber 0.5% by volume (39.2 kg/cu. m, 66 lbs./cu. yd.)	Other Synthetic 0.1% by volume (0.9 kg/cu. m, 1.5 lbs./cu. yd.)
Materials			
• Corrosion resistant	Yes	No	Yes
• Non-rusting (no rust coloration to surface)	Yes	No	Yes
• Chemically inert	Yes	No	Yes
• Non-magnetic	Yes	No	Yes
• Protrusions are non-hazardous	Yes	No	Yes
Mix Proportions, Design and Mixing			
• Fiber dosage can be tailored to achieve concrete structural performance enhancements	Yes	Yes	No
• Use standard mixer equipment	Yes	Yes	Yes
• Rapid uniform dispersion into mix at volume loadings greater than 1%	Yes	No	No
• Volume loadings up to 3%	Yes	No	No
Concrete Performance			
• Higher green strength	Yes	Yes	Minimal
• Higher impact strength	Yes	Yes	Minimal
• Higher ductility	Yes	Yes	Minimal
• Increased toughness (ASTM/JSCE)	Yes	Yes	Minimal
• Higher post-crack load carrying capacity	Yes	Yes	Minimal
• Increased flexural fatigue strength	Yes	Yes	Minimal
• Increased durability - crack resistance	Yes	Yes	Minimal
• Shrinkage crack control	Yes	Yes	Minimal
• Plastic shrinkage crack control	Yes	Yes	Yes

3M fibers do not affect concrete hydration characteristics and are compatible with all concrete mixes and admixtures.

3M fibers have been used for cast-in-place concrete such as: highway pavements, white toppings, bridge deck overlays, curbs, driveways and sidewalks. 3M fibers are suitable for other cast-in-place, precast and shotcrete applications. Contact 3M for more information.

There are many advantages and benefits of using 3M fibers. See table above for more information.

Composition and Materials: 3M fibers are non-metallic polyolefin. See Table 1.

Applicable Standards: 3M fibers have been tested according to the following methods:

American Society for Testing and Materials (ASTM)

- ASTM C 469 — Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
- ASTM C 1018 — Test Method for

Flexural Toughness and First-Crack Strength of Fiber Reinforced Concrete (Using Beam with Third Point Loading)

- ASTM C 1116 — Standard Specification for Fiber-Reinforced Concrete and Shotcrete
- Vebe Slump Test and Vebe Time Test (Recommended by ACI Committe 544)
- Impact Strength (Recommended by ACI Committee 544)

Tests using Japanese methods were also run on 3M fibers according to the following:

Japan Society of Civil Engineers (JSCE)

- JSCE III-1 Standard, Specification of Steel Fibers for Concrete, Concrete Library No. 50, March 1983
- JSCE-SF4 Standard for Flexural Strength and Flexural Toughness, "Method of Tests for Steel Fiber Reinforced Concrete," *Concrete Library of JSCE,* No. 3, June 1984, pp. 58-66

Japan Concrete Institute (JCI):

- "Standard Test Method for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete, (Standard SF4)," *JCI Standards for Test Methods of Fiber Reinforced Concrete,* Japan Concrete Institute, 1983, pp. 45-51

2. Technical Data

3M fibers meet the material and performance requirements of ASTM C 1116, Type III.

JSCE and JCI standards especially show strength and toughness enhancements to concrete when using 3M fibers. Specific testing results are available upon request.

Assistance is available to help designers in achieving desired performance when using 3M fibers.

Table 1 — Typical Physical Properties of 3M Polyolefin Fibers

Property	Results
Specific Gravity (Bulk Relative Density)	0.91
Tensile Strength	275 MPa (40,000 psi)
Modulus of Elasticity	2647 MPa (384,000 psi)
Elongation at Break	15%
Ignition Point	593°C (1100°F)
Melt Point	160°C (320°F)
Chemical and Salt Resistance	Excellent
Alkaline Resistance	Excellent
Electrical Conductivity	Low

See Technical Services for more information.

3. Installation

Methods of Use: For information on mix proportions and design, placement and finishing, see separate Guide Specifications for either Cast-in-place Concrete, Precast Concrete or Wet Mix Shotcrete.

4. Availability and Cost

Contact manufacturer for availability. In-place cost may vary due to regional and other considerations.

5. Warranty

3M MAKES NO WARRANTIES, EXPRESSED OR IMPLIED, INCLUDING BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. Many factors beyond the control of 3M can affect the use and performance of 3M polyolefin fibers in a particular application, including materials to be mixed with the 3M product, the preparation of those materials, and the time and conditions under which the product is used. Since these factors are uniquely within the user's knowledge and control, it is essential that the user evaluate the 3M polyolefin fibers to determine whether this product is fit for the particular purpose and suitable for user's application. LIMITATION OF REMEDIES AND LIABILITY: if the 3M product is proved to be defective, THE EXCLUSIVE REMEDY, AT 3M'S OPTION, SHALL BE TO REFUND THE PURCHASE PRICE OF OR REPLACE THE DEFECTIVE 3M PRODUCT. 3M shall not otherwise be liable for any injury, losses or damages, whether direct, indirect, special, incidental, or consequential, regardless of the legal theory asserted, including tort, contract, negligence, warranty, or strict liability.

6. Technical Services

3M provides assistance to help determine appropriate 3M fibers dosage, mix proportions and design, batching and field placement. 3M will provide assistance on specific projects from design through construction when using 3M fibers.

Table 2 — Fiber Types and Application Recommendations

3M Fiber Types (length by diameter)	Package Size and Type	Cast-in-Place	Wet Mix Shotcrete	Precast Concrete
50/63 (50 mm by 0.63 mm) (2 inches by 25 mils)	11.3 kg (25 lbs) box fibers wrapped in bundles	Yes	No	Yes
25/38 (25 mm by 0.38 mm) (1 inch by 15 mils)	9 kg (20 lbs.) box fibers wrapped in bundles	Yes	Yes	Yes

3M

Polyolefin Fibers Team
3M Center 251-2A-09
St. Paul, MN 55144-1000
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3M

Polyolefin Fibers

Technical Data

The information contained herein is from testing conducted under contract by the South Dakota School of Mines and Technology for the South Dakota Department of Transportation and is described in detail in study SD94-04. The concrete specimens tested were from actual full depth placements.

These test results show that 3M fibers improve hardened concrete material performance characteristics like steel fibers do. This is significant because 3M fibers combine the structural advantages of steel fibers and the material advantages of polyolefin.

The data presented is based on the concrete mix in Tables 1 and 2.

Summary of Typical Test Results Included:

- **Toughness** (ASTM and JCI Standards) — Results based on the load/deflection curve show elastic/plastic behavior of 3M fiber reinforced concrete (FRC) and post-crack load carrying capacity similar to steel FRC.
- **Flexural Strength** — 3M FRC increased the ability of concrete to withstand loads in flexure by approximately 13%.
- **Fatigue Strength/Endurance** — 3M FRC was able to endure two million fatigue cycles at a load similar to steel FRC, approximately 30% greater than plain concrete.
- **Impact Strength** — 3M FRC was over two times greater than steel FRC for failure due to impact loads and almost 14 times greater than plain concrete.
- **Crack Width Comparison** — Average crack width was reduced from 12.3 mils for plain concrete to 3.6 mils for 3M FRC.
- **Compressive Strength** — 3M fibers do not significantly affect compressive strength.

Table 1 — Concrete Mixes and Proportions

Mixture Type	Fiber Diameter	Fiber Length	Water/ Cement Ratio	Cement lbs/cu. yd.	Fly Ash lbs/ cu. yd.	Coarse Aggregate lbs./cu. yd.	Fine Aggregate lbs./cu. yd.	Fibers lbs. cu. yd. (vol. %)	Water lbs./cu. yd.	AEA oz./cu. yd.
Plain Concrete	NA	NA	0.47	519	114	1770	1270	0	242	15.0
Steel FRC	0.8 mm	59 mm	0.50	525	113	1634	1331	66 (0.5%)	263	11.5
3M FRC	0.63 mm	50 mm	0.50	525	113	1634	1331	25 (1.6%)	263	11.5

Table 2 — Properties of Fresh Concrete

Mixture Type	Unit Weight lbs./cu. ft.	Slump (inches)	Air Content (%)
Plain Concrete	147.08	1.25	6.6
Steel FRC	148.73	3.25	4.5
3M FRC	145.85	0.25	4.9

Toughness — ASTM and JCI Standards

1. Test Standards and Methods

• ASTM C 1018 — Test Method for Flexural Toughness and First Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading),

• JSCE-SF4 Standard for Flexural Strength and Flexural Toughness, "Method of Tests for Steel Fiber Reinforced Concrete," *Concrete Library of JSCE*, No. 3, June 1984, Japan Concrete Institute (JCI), pp. 58-66.

• "Standard Test Method for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete, (Standard SF4)," *JCI Standards for Test Methods of Fiber Reinforced Concrete*, Japan Concrete Institute, 1983, pp. 45-51

2. Significance of Test

These tests were designed to show the ductile, elastic/plastic behavior and post-crack load carrying capacity of fiber reinforced concrete.

The results of these tests yield load deflection curves, toughness indices, ratios and factors that indicate how fiber concrete can be expected to perform under static flexural loads.

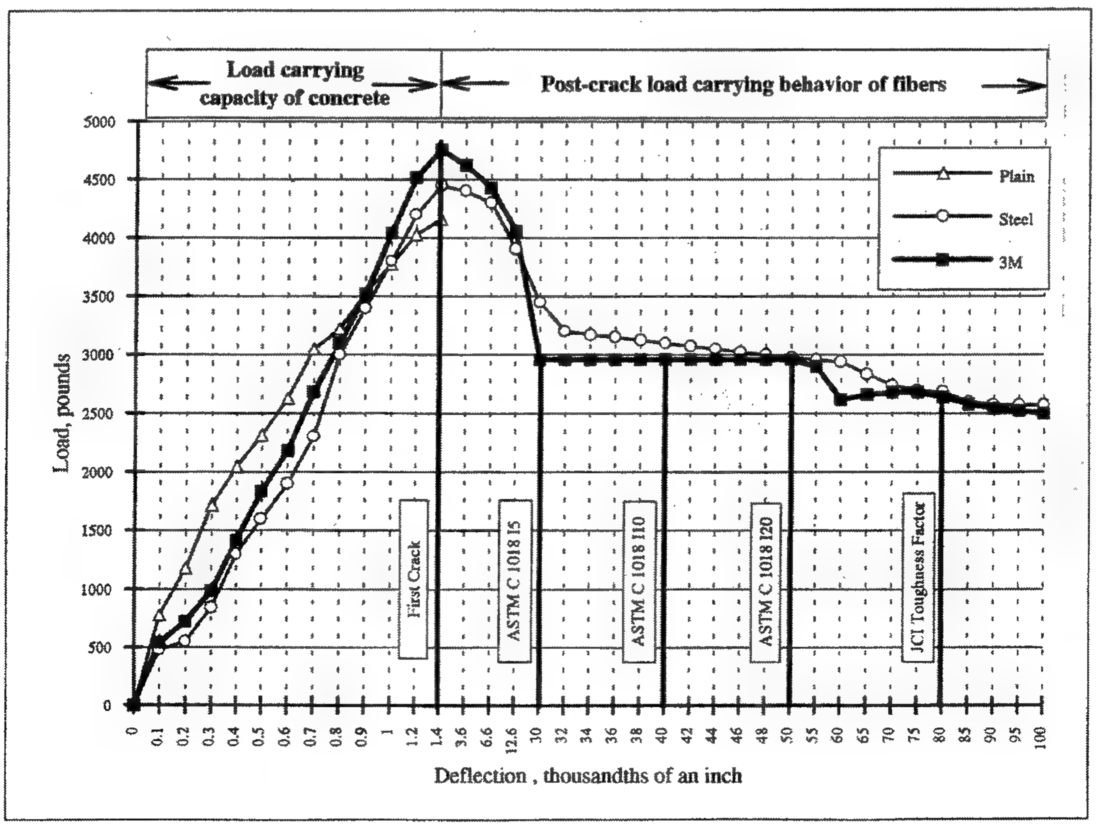
3. Test Results

The results show that steel fibers and 3M fibers produce similar substantial toughness improvements to concrete.

Figure 1 — Load Deflection Curve below shows the plastic (ductile) behavior of concrete using steel fibers and 3M fibers compared to the brittle behavior of plain concrete. Both steel FRC and 3M FRC provide significant post-crack load carrying capacity.

Toughness indices and ratios are calculated based on the area under the load deflection curve and are an indication of the FRC's ductility and toughness. The toughness indices and ratios are slightly higher for 3M FRC indicating that it is more ductile and tougher than steel FRC. Both steel FRC and 3M FRC have toughness ratios near two, which indicates near perfect plastic behavior. See Figures 2 and 3 on the next page.

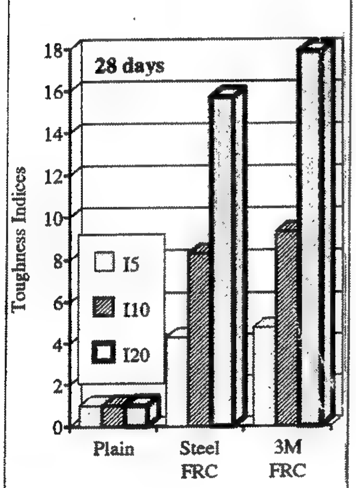
Figure 1 — Load Deflection Curves



4. **Test Comparisons**
   Improvement in toughness is a desirable property because it indicates increased energy absorption capacity to failure and ductile mode of failure. It provides increased resistance to dynamic and impact loads such as earthquakes, blasts and suddenly applied loads.

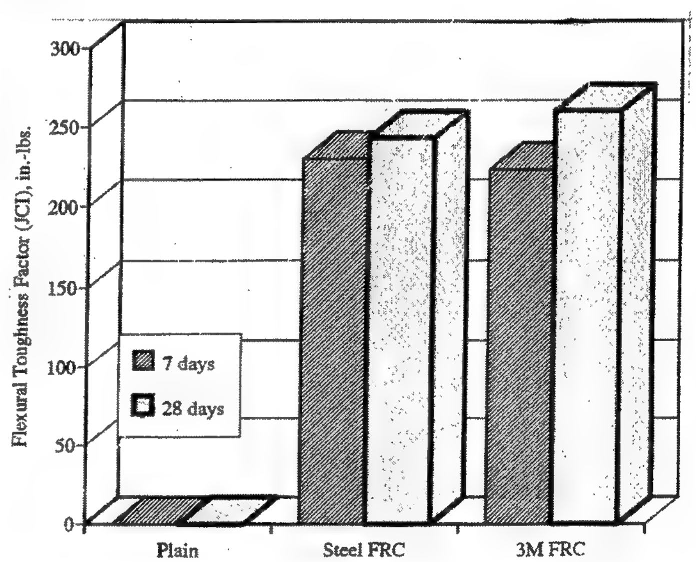
5. **Property Improvement Benefits**
   3M fibers significantly improve toughness properties of concrete similar to using steel fibers but 3M fibers also have the benefit of being a synthetic material.
   Improved toughness relates to increased durability, increased service life, increased crack resistance and post-crack load carrying capacity.
   All concrete cracks. Once plain concrete cracks, the concrete fails to carry any load across the cracks. 3M fibers give concrete the ability to carry loads even when cracked. Other synthetic fibers do not exhibit the significant resistance to flexural cracking and increased post-crack load carrying capacity that steel and 3M fibers do.
   These property improvements help concrete last longer and help reduce maintenance. That means the service life of a structure may be significantly increased and costly replacement may be delayed. 3M fibers may also help reduce initial construction cost.

Figure 2 — Toughness Indices



This chart is an analysis of the load deflection curve. These toughness indices evaluate the early load behavior of the fiber concrete beyond the first crack point. 3M FRC has slightly higher indices indicating slightly better early post-crack load carrying capacity (elastic/plastic behavior) than steel FRC.

Figure 3 — JCI Flexural Toughness Factor



This chart is an analysis of the load deflection curve and compares the energy that is required to deflect the test beam to 0.08 inches (1/150th of the span). This JCI standard evaluates post-crack load carrying capacity much farther beyond the ASTM C 1018 toughness indices and therefore it shows how well 3M FRC and Steel FRC performs at loads and deflections well beyond those experienced at first crack, I5, I10 or even I20. Other synthetic fibers typically do not exhibit any significant behavior beyond I5 or I10 and usually the load carrying capacity is much lower.

Modulus of Rupture (Static Flexural Strength)

1. Test Standards and Methods

ASTM C 78 Test Method for Flexural Strength of Concrete

2. Significance of Test

This test determines the ability of 3M FRC to withstand static loads that will cause deflection and then cracking in the concrete as compared to plain concrete and steel FRC.

3. Test Results

These results show that 3M FRC improved early strength against cracking similar to steel FRC.

4. Test Comparisons

Modulus of rupture is shown on the load deflection curve as the maximum load (first crack). See Figure 1.

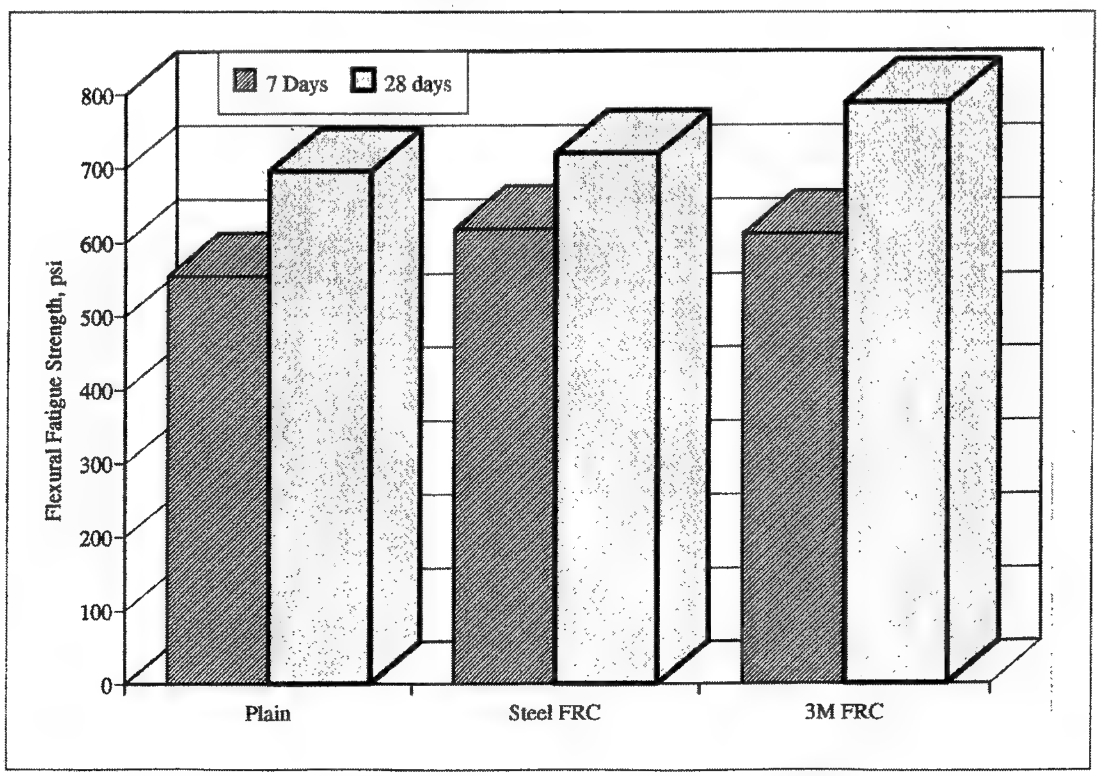
Also, since modulus of rupture is measured at the load when first crack occurs, compare these results to first crack results shown in Figure 6 Impact Strength.

5. Property Improvement Benefits

3M fibers improve concrete modulus of rupture as compared to plain concrete and similar to improvements by steel fibers.

A higher modulus of rupture shows that the fibers can help concrete resist cracking due to non-moving loads that may be placed on it during service such as: equipment in manufacturing plants or on offshore drilling platforms, inventory in warehouses, stationary vehicles in parking ramps, stationary airplanes in hangars, water in treatment and storage facilities and the dead load of the structure itself.

Figure 4 — Modulus of Rupture



Fatigue Strength and Endurance

1. Test Standards and Methods

ACI 544.2R.89 Flexural Fatigue Endurance and ASTM C 78 Test Method for Flexural Strength of Concrete

2. Significance of Test

The greatest advantage to adding fibers to concrete is the improvement of fatigue characteristics.* In many structures flexural fatigue strength and endurance limits are needed properties. Thus a new material like 3M fibers needs to show performance improvements in this test. These properties are useful in designs requiring structural concrete members to perform satisfactorily under high stress levels subjected to a large number of load cycles. Fatigue specimens were tested for 60 day modulus of rupture before fatigue cycle loading.

Test specimens were subjected to two million load cycles at 20 cycle per second. The loads applied during fatigue cycling were a minimum of 10% of pre-fatigue modulus of rupture and a maximum of 50% to 85% of the pre-fatigue modulus of rupture. Two million cycles is believed to represent typical life span fatigue loading.

3. Test Results

The chart below shows the maximum flexural stress that could be endured for two million fatigue cycles and the flexural strength before fatigue testing. The steel FRC has a slightly higher maximum flexural fatigue stress than 3M FRC although they both perform similarly when compared to plain concrete.

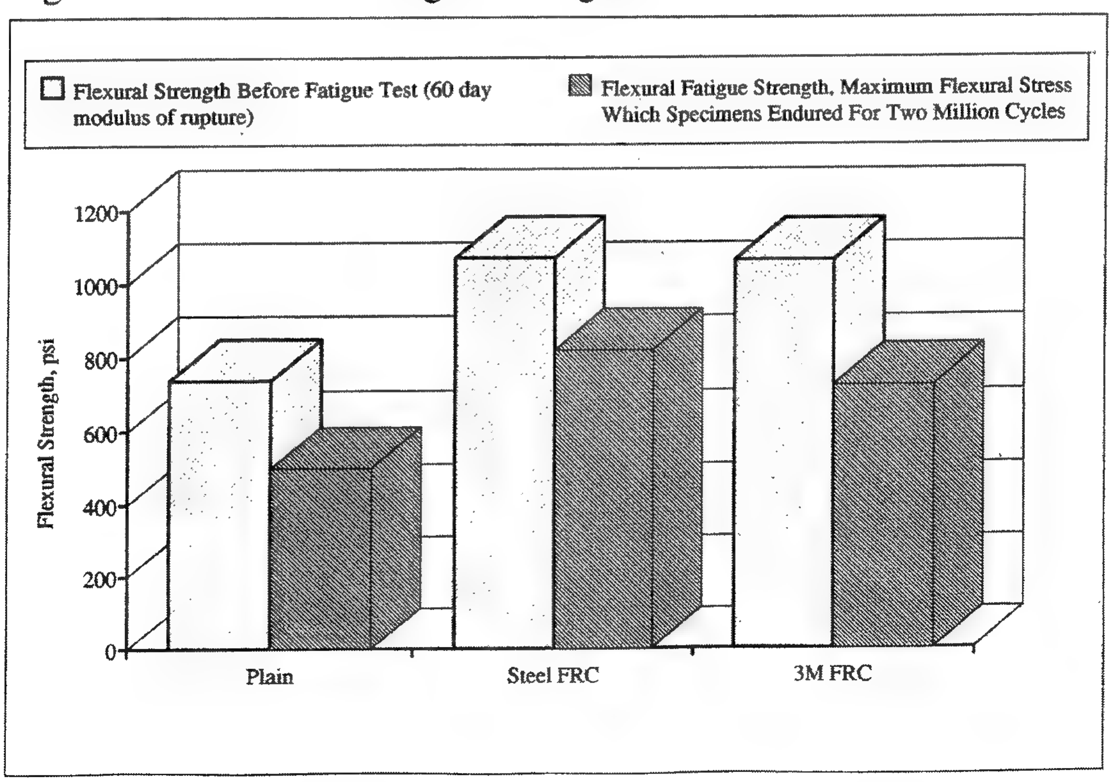
4. Test Comparisons

Modulus of rupture was tested before the fatigue test at 60 days to establish the upper and lower limits of the repetitive fatigue loading instead of using the 28 day test due to the increase in strength at 60 days. Compare with figure 4.

5. Property Improvement Benefits

3M FRC helps concrete to better endure fatigue cycling. Many structures require high fatigue strength. This property allows for maintaining the same section depth and gaining greater fatigue endurance or reducing the section depth for the same life span or both. Reduced cracking, reduced maintenance and longer concrete life may help reduce life cycle cost of structures. The potential to reduce section depth may also help reduce installation cost.

Figure 5 — Flexural Fatigue Strength



Impact Strength

1. Test Standards and Methods

ACI 544.2R.89 Impact Strength

2. Significance of Test

Shows the ability of concrete to withstand cracking and failure due to repeated impact loads.

3. Test Results

The comparison in the chart below shows that plain concrete has very low resistance to cracking and failure due to impact. The addition of fibers improves resistance to first crack and ultimate failure. There is a significant improvement in the ultimate impact resistance after first crack showing that the fibers efficiently absorb energy and carry the load. 3M fibers showed the greatest improvement in first crack strength and ultimate failure resistance. Impact resistance of 3M fibers shown in the chart below is over two times greater than steel fibers.

4. Test Comparisons

Compare toughness results to the improvement shown below to impact strength after first crack.

5. Property Improvement Benefits

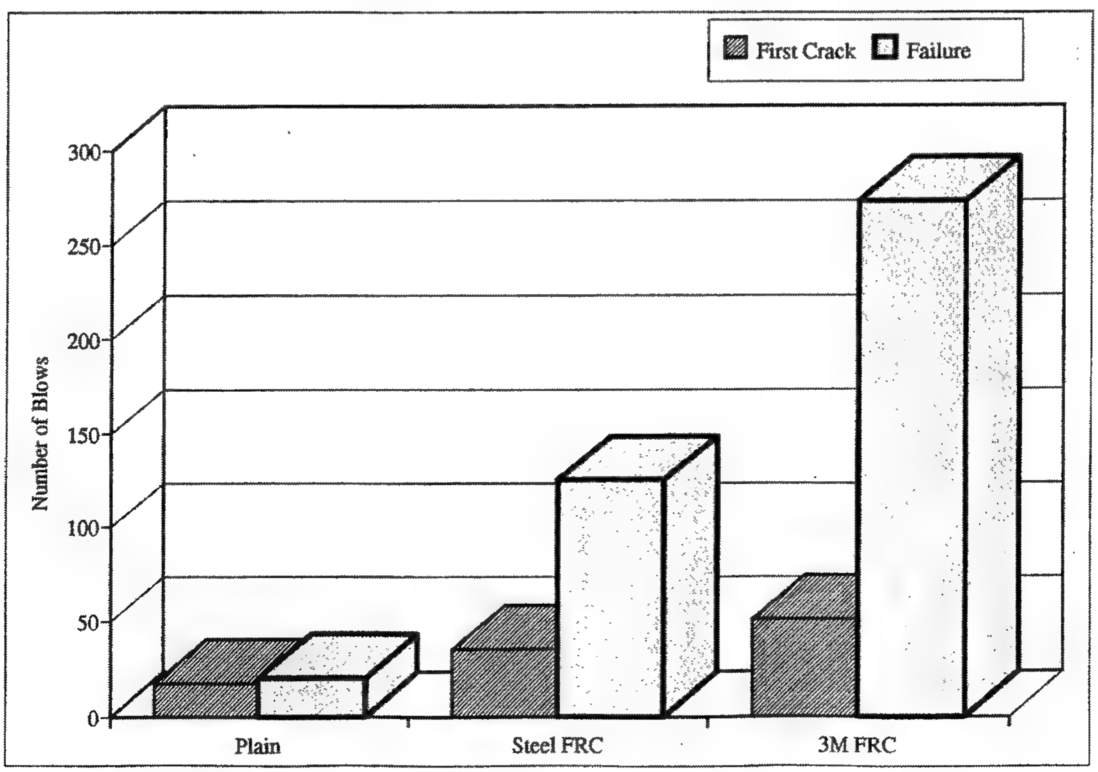
Concrete made with 3M fibers has greater resistance to fracture and failure due to heavy impact loads and thus is more energy absorbing when compared to plain concrete or steel FRC.

This improved impact resistance of 3M FRC means greater resistance to cracking or failure in such applications as:.

- Airport runway pavements — airplane landings.
- Warehouse floors — loading and unloading, heavy equipment impact
- Manufacturing Plants — impact from vibration of heavy equipment

Crack resistance means longer concrete life and reduced maintenance which may help reduce initial installation cost and life cycle costs.

Figure 6 — Impact Strength



Crack Width Comparison

1. Test Standards and Methods
ACI Committee 224 Recommendations

2. Significance of Test
This is an evaluation of actual cracks that occurred as compared to ACI 224 recommended maximum allowable crack widths.

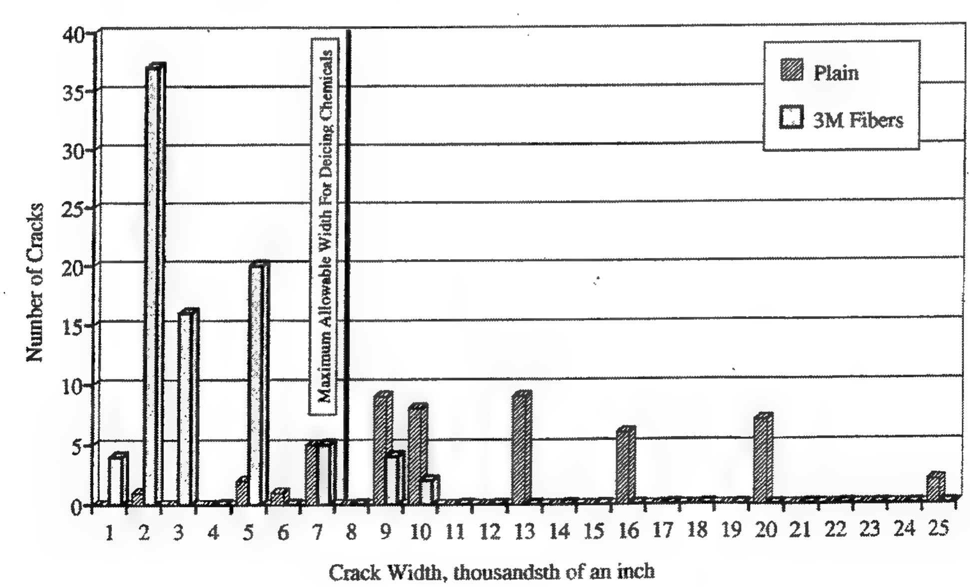
3. Test Results
The figure below shows that 93% of cracks that did occur in 3M FRC were under 0.007 inches compared to only 18% under 0.007 inches for plain concrete. The 0.007 inch width is the ACI recommended tolerable crack width for exposure to deicing chemicals.

4. Test Comparisons
Impact strength, toughness, static flexural strength and fatigue endurance are all related to crack width because each of these tests identifies the point at which cracking occurs. For example, the load deflection curve identifies first crack. This comparison shows what fibers do to control crack width once the first crack appears.

5. Property Improvement Benefits
When cracking does occur, 3M FRC helps reduce crack width. Since all concrete cracks, controlling crack width once cracks occur helps to decrease concrete permeability which will help decrease the ability of corrosion causing agents to penetrate into the concrete. Controlling crack width directly affects maintenance and concrete life. Decreasing crack width helps increase service life.

Furthermore, smaller crack widths contribute to the increased toughness, fatigue endurance and impact strength discussed earlier. See related tests for more information on benefits.

Figure 7 — Crack Widths, Plain vs. 3M FRC



Compressive Strength

1. **Test Standards and Methods**
   ASTM C 39 — Cylinder Compressive Strength and Static Modulus

2. **Significance of Test**
   Determine compressive strength of concrete samples

3. **Test Results**
   During the compression test plain concrete cylinders failed instantly (brittle failure) shattering into pieces with a loud noise at the first crack while the fiber concrete cylinders continued to sustain the load and underwent large deformations without disintegrating into pieces. The concrete was held together by the fibers.

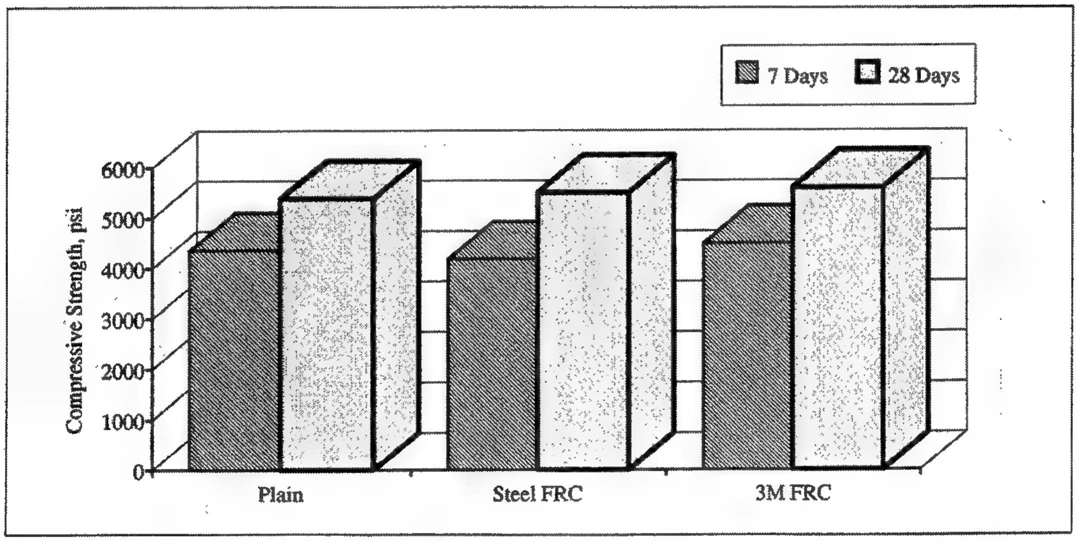
   A visual observation of the ultimate failure of the cylinders in compression indicated that the 3M FRC specimens were more ductile than the steel fiber specimens.

   Typically adding any fiber to concrete does not increase compressive strength but some fibers at higher volume loadings can reduce compressive strength. The significance of these results is plain concrete, 3M FRC concrete and steel FRC compressive strengths were similar.

4. **Test Comparisons**
   Each of the other properties of 3M FRC discussed in this data sheet can affect compressive properties because 3M fibers change the failure mode from brittle to ductile as described previously.

5. **Property Improvement Benefits**
   Fibers, including 3M fibers, do not significantly affect concrete compressive strength. So, when using 3M fiber concrete compressive strength design criteria can be established or maintained. Maintaining compressive strength while adding ductility means that even concrete subject to compressive loads will benefit from the property enhancements discussed in this data sheet. See other test descriptions for benefits information.

Figure 8 — Compressive Strength



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Polyolefin Fibers

For Use in Cast-in-Place Concrete

Guide Specification

NOT FOR USE AS A CONSTRUCTION DOCUMENT. Edit carefully to coordinate with specific project requirements. User must determine suitability of this guide specification in whole or part for a particular project.

SECTION 03241

POLYOLEFIN FIBER REINFORCEMENT

PART 1 GENERAL

1.01 SECTION INCLUDES

A. Polyolefin fiber reinforcement for cast-in-place concrete.

1.02 RELATED SECTIONS

A. Section 03300: Cast-in-Place Concrete.

1.03 REFERENCES

A. American Society for Testing and Materials (ASTM)
  1. ASTM C 1116 Standard Specification for Fiber Reinforced Concrete and Shotcrete
  2. ASTM C 1018 Standard Test Method for Flexural Toughness and First Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third Point Loading)

B. American Concrete Institute (ACI)
  1. ACI 544.1R State of the Art Report on Fiber Reinforced Concrete
  2. ACI 544.2R Measurement of Properties of Fiber Reinforced Concrete

C. Japan Society of Civil Engineers (JSCE): JSCE-SF4 Standard for Flexural Strength and Flexural Toughness, "Method for Steel Fiber Reinforced Concrete," *Concrete Library of JSCE*, No. 3, June 1984, pp. 58-66

1.04 SUBMITTALS

A. Submit two copies of manufacturer's literature for fibers including product data, brochures, guide specifications written batching and mixing instructions and appropriate Material Safety Data Sheets (MSDS).

B. Submit [______] copies of a certificate prepared by concrete supplier, under provisions of Section [01400] [______], stating that the specified fibers were added to each batch of concrete delivered to the project site. Each certificate should be accompanied by one copy of each batch delivery ticket indicating product name, manufacturer and quantity of fiber reinforcement added to each concrete load.

1.05 QUALITY ASSURANCE

A. Manufacturer: Provide technical assistance from design through construction for use of fiber reinforcement.

A field mock-up may not be needed for every project. Delete Paragraph B if a mock-up is not necessary.

B. Mock-Up: Provide mock-up(s) of concrete using fiber reinforcement specified in this Section. Mock-up(s) shall be representative of Work of Related Sections and techniques specified in this Section. Mock-up(s) is (are) to be approved by [architect/engineer] [owners representative]. Use mock-up(s) for reference during project.

1.06 DELIVERY, STORAGE AND HANDLING

A. Deliver fiber reinforcement in sealed, undamaged containers with labels intact and legible, indicating material name and lot number.

B. Deliver fiber reinforcement to location where it will be added to each truck load.

C. Store materials covered and off the ground. Do not allow boxes to become wet.

PART 2 PRODUCTS

2.01 MANUFACTURER

A. 3M Polyolefin Fibers Team, 3M Center 251-2A-09, St. Paul, MN 55144-1000, (612) 737-9705

2.02 MATERIALS

Paragraph A below specifies fiber type 50/63, 50 mm length by 0.63 mm diameter (2 inches length by 25 mils diameter) which is preferred for cast-in-place applicaitons. However, fiber type 25/38, 25 mm length by 0.38 mm diameter (1 inch length by 15 mils diameter) may also be used.

A. Fiber Reinforcement: 3M™ polyolefin fibers type 50/63, non-metallic monofilament fibers with the following typical physical properties:
1. Specific Gravity (Bulk Relative Density): 0.91
2. Tensile Strength: 275 MPa (40,000 psi)
3. Modulus of Elasticity: 2647 MPa (384,000 psi)
4. Elongation at Break: 15 percent
5. Ignition Point: 593 degrees Celsius (1100 degrees Fahrenheit)
6. Melt Point: 160 degrees Celsius (320 degrees Fahrenheit)
7. Chemical, Salt and Alkaline Resistance: Excellent
8. Electrical Conductivity: Low

Edit toughness index in Paragraph B if 2.03 Paragraph A is not specified. Contact manufacturer for assistance.

B. Fiber reinforcement provided in this section shall produce concrete conforming to the requirements for each type and class of concrete required, as indicted on drawings, and in Section [03300] and requirements of:
1. ASTM C 1116: Type III
2. ASTM C 1018: Toughness Index I_{10}: 9.0 and I_{20}: 17.0
3. JSCE-SF4 Toughness Factor: 28.25 Nm (250 in-lbs.)

2.03 MIXES

Coordinate fiber loading with mix proportions and design specified in Section 03300 Cast-in-Place Concrete. Other fiber dosages than those specified are possible to meet specific project requirements. Increasing fiber loading may reduce slump compared to non-fiber reinforced concrete. Contact manufacturer for technical assistance to determine fiber loading, mix proportions and design. Fiber balls do not usually occur when using 3M fibers. If balling has occured, it is due to mix proportion, equipment and/or procedures.

A. To avoid the formation of fiber balls, do not unwrap or open fiber bundles. Fiber reinforcement bundles must be intact when added to concrete mix.

Paragraph B below specifies 3M's recommended fiber reinforcement dosage for normal concrete mix proportions (60/40 coarse/fine aggregate ratio) to obtain concrete structural material property improvements that are similar to steel fiber at 39.2 kilograms per cubic meter (66 pounds per cubic yard). This dosage also provides plastic shrinkage crack control.

B. Add fiber reinforcement at 14.5 kilograms per cubic meter (25 pounds per cubic yard), approximately 1.6 percent by volume, after concrete has been loaded into truck.

C. Add fiber reinforcement with drum turning.

D. Once fiber reinforcement has been added, turn truck drum at ACI established mixing speed one minute. Back concrete up to discharge end of drum then take concrete back down into drum and mix one minute for each inch of slump but not less than 4 minutes at ACI established mixing speed.

Retain Paragraph E only for fiber reinforcement loading greater than 1.6 percent by volume (14.5 kilograms per cubic meter, 25 pounds per cubic yard of concrete) otherwise delete Paragraph F.

E. Truck load must not exceed 80 percent of rated capacity when using fiber reinforcement.

F. If truck drum contains less than 50 percent capacity, back concrete up to top of discharge end of drum and put fiber reinforcement directly on top of concrete before mixing.

The following only describes requirements specific to using 3M Fiber. Other requirements for mix proportions and design, placement and finishing should be specified in Section 03300 Cast-in-Place Concrete.

PART 3 EXECUTION

3.01 PLACEMENT

A. Place concrete in accordance with provision of Section 03300 Cast-in-Place Concrete and with additional instructions as follows.

B. Avoid using rakes or other tools that will align fibers or disrupt uniform fiber dispersion when moving concrete.

C. Using flat tined pitch forks (potatoe fork) may be useful for moving low slump concrete.

Fiber balls do not usually occur when using 3M fibers. If balling has occured, it is due to mix proportion, equipment and/or procedures.

D. Remove fiber balls from mix if they occur.

3.02 FINISHING

A. Using a roller bug (rolling jitter bug) screed to bury fiber reinforcement near surface may make final finishing easier.

B. Hand Finishing: use steel/magnesium tools.

C. Broom Finishing: use a stiff bristle broom. Hold broom so that bristles lie flat on surface. Avoid positioning bristles perpendicular to surface. Pull broom in one direction, do not push.

D. After concrete has cured, protruding fibers are readily removed (if desired for aesthetics) by using a typical weed burner.

3.03 SCHEDULES

A schedule may be needed to coordinate fiber dosage specified in this section with drawings indicating areas for each fiber dosage type especially if more than one fiber dosage is specified in this Section.

END OF SECTION

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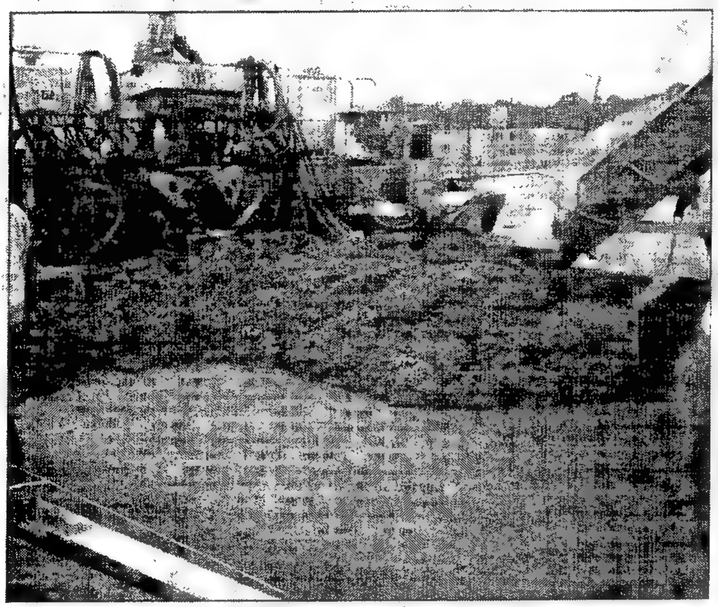
Polyolefin Fibers Case History

White Topping — Loray Dr., No. Mankato, MN



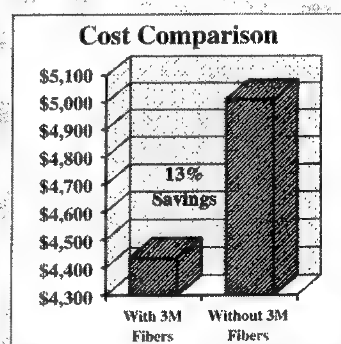
Using 3M fibers saved 13% compared to the cost of using a thicker plain concrete white topping and provided a crack controlled surface.

1. Project Description

- ***Owner:*** MN DOT
- ***Concrete Supplier:*** P.C.I. Progressive Contractors Inc., Mankato, MN
- ***Designer:*** MN DOT
- ***Placement Date:*** June 1996.
- ***Features & Requirements:*** MN DOT wanted to transfer responsibility for this road to the City of North Mankato in a crack controlled condition by applying a cost effective white topping that would not crack.
- ***Why 3M Fibers Were Used:*** 3M fibers allowed MN DOT to use a white topping instead of complete road replacement. This was possible because 3M fibers allowed a thinner white topping section making it the least expensive alternative on a first cost basis (see cost details on back page), provided life cycle cost reductions and performance improvements (such as improved toughness and crack control) needed to provide a crack controlled surface.

2. Job Execution

- ***Preparation:*** Typical preparation for a white topping was not changed by using 3M fibers.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was used at 1.67 volume percent and was added to the concrete using a portable batch plant and hauled to the site using agitated dump trucks.
- ***Concrete Placement:*** The concrete was placed using a slipform paver and a vibrating screed for small, odd-shaped areas. The fiber reinforced concrete placed and finished with no problems in mixing, handling or finishing.
- ***Whitetopping Area:*** approximately 7,000 sq. ft. (777 sq. yd.)



- ***Observations:*** MN DOT cut more joints than may have been required to avoid any possibility of cracking.

3. Results/Conclusions

A cost effective, crack-controlled repair of an old asphalt surface.

White Topping Cost Comparison

Reinforcement	Plain		Plain		3M fibers	
Thickness	6 inches		4.5 inches		3 inches	
Joint space/lineal feet of joint	10 feet by 12 feet 340 feet		5 feet by 6 feet 780 feet		5 feet by 6 feet 780 feet	
Concrete (M) $75/cy	$	3.333	$	2,500	$	1,667
Cold planning & cleaning (LE) $1.69 sy/3 in. p.63	$	901	$	676	$	451
3M Polyolefin fibers (M) $50.25/cy		NA		NA	$	1,117
Handling fibers (L) $5/cy		NA		NA	$	111
Sawcuts T/4 (LME) $1.18/lf/in D p. 27	$	602	$	1,035	$	690
Hot pour sealing (LM) $0.51/lf p. 64	$	173	$	398	$	398
Total Cost		**$5,010**		**$4,609**		**$4,433**
Percent over 3M fiber cost		**+13%**		**+4%**		**NA**
Difference between 3M fibers Cost	$	**577**	$	**176**		**NA**

Note: L=Labor, M=Materials, E=Equipment. When a page number is cited above it is the source in "Means Site Work & Landscape Cost Data 1995."

The cost comparison information provided above is based on a 2400 sq. ft. representative area.

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Polyolefin Fibers Case History

White Topping — US Hwy 83, SD

3M fibers were found to enhance desired structural properties including toughness, ductility and impact strength; making 3M FRC white toppings more durable and more efficient than plain concrete overlays.

1. Project Description

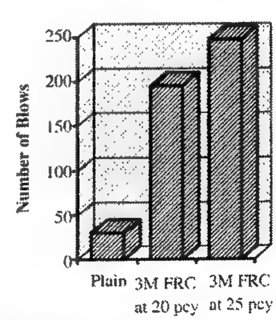
This project is located on the North approach to the US Hwy 83 bridge structure over I-90 south of Pierre, SD (structure number 43-026-195) mile marker 212.

- ***Owner:*** South Dakota Dept of Transportation (SDDOT)
- ***Concrete Supplier:*** Rosebud Concrete Ready Mix, Presho Plant
- ***Designer:*** SDDOT and Dr. Ramakrishnan, South Dakota School of Mines and Technology
- ***Placement Date:*** Sept/Oct 1994
- ***Features & Requirements:*** SD DOT requires road surface renovation techniques and materials that are effective and economical. This bridge approach section had a major two inch wide transverse crack and other shorter cracks greater than one inch wide. These cracks were presumed to extend full depth.
- ***Why 3M Fibers Were Used:*** Non-metallic, 3M fibers allow thinner toppings and performance improvements (such as improved toughness and crack control) needed to provide a crack controlled surface, especially to control reflective cracking over the existing large cracks.

2. Job Execution

- ***Preparation:*** Typical preparation for a white topping was not changed by using 3M fibers. The asphalt was scarified to a depth ranging from 2½″ to 4½″.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was used at 20 pcy (1.3%) and 25 pcy (1.67%)(see table on back page for more information).
- ***Concrete Placement:*** The West side used 3M fibers at 25 pcy. The East side used 3M fibers at 20 pcy. A vibrating screed and a hand vibrator were used for consolidation. Only one joint was sawcut into the white topping.
- ***White Topping Size:*** Two panels 14′ by 50′ each. One contained fibers at 20 pcy and one 25 pcy.

Comparison of Impact Strength



- ***Observations:*** The concrete had adequate workability. The concreting, finishing and tining operations went without any problems.

3. Results/Conclusions

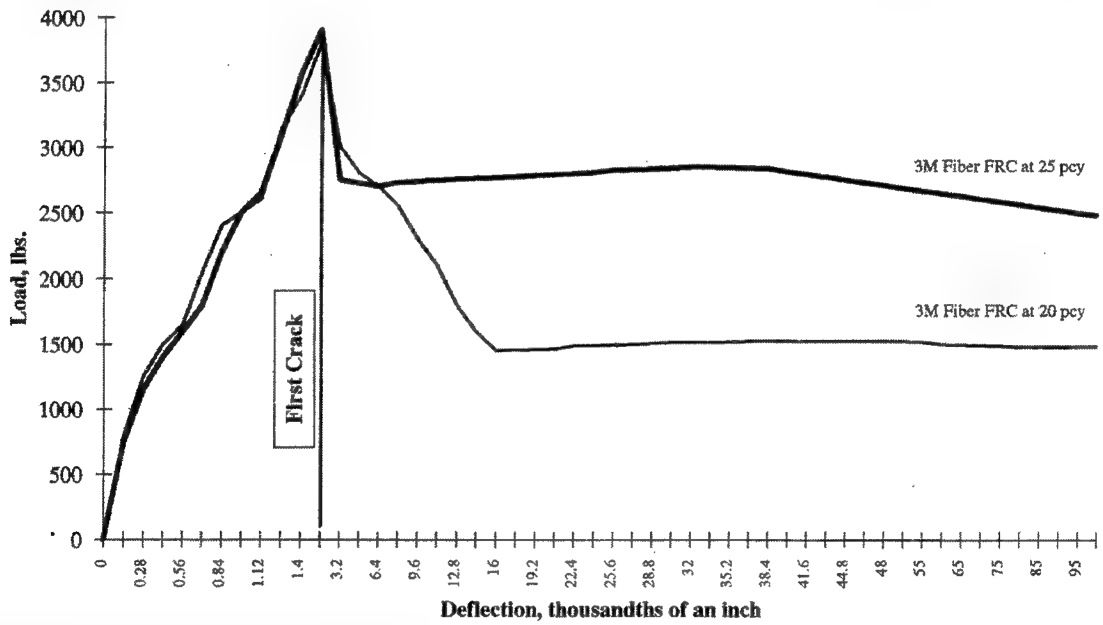
A comparison of the load deflection curves for 20 pcy vs. 25 pcy of 3M fibers showed that more fibers helps increase the toughness and ductility of the concrete. All the measured toughness characteristics show the addition of 3M fibers considerably increased the toughness of the concrete. The ASTM toughness indices I5, I10 and I20 were more than 4, 8 and 14 times greater than that of typical plain concrete. The toughness ratios of 1.8 and 1.7 indicate the concrete was very ductile.

The impact strength was increased considerably due to the addition of 3M fibers. The average number of blows to failure were 248 for 25 pcy 3M fibers and 195 for 20 pcy 3M fibers. Although plain concrete was not used as a control for this white topping, previous SD DOT tests comparing plain concrete to 3M FRC suggest that plain concrete can withstand approximately 25 to 30 blows before failure.

Inspections of the white topping conducted after two years showed there was one crack in the 20 pcy 14′ by 50′ panel at about 20′ from the bridge, but this crack did not pass through the 25 pcy slab and was not reflective. No cracks existed over the large cracks in the asphalt indicating no reflective cracking. There seemed to be a good bond. There was no damage or distress on the surface.

As a result of this experience using 3M FRC for white topping (thin or thick overlays), SD DOT intends to do additional testing on a larger scale. These fibers were found to enhance desired structural properties making white toppings more durable and more efficient than plain concrete overlays.

Comparison of Load Deflection Curves



Concrete Mixes and Proportions

Mixture Type	Fiber Diameter	Fiber Length	WC (WC+FA) Ratio	Cement lbs/cu. yd.	Fly Ash lbs./cu./ yd.	Coarse Aggregate lbs./cu. yd.	Fine Aggregate lbs./cu. yd.	Fibers lbs. cu. yd. (vol. %)	Water lbs./cu. yd.	AEA oz./cu. yd.
3M FRC	0.63 mm	50 mm	0.51 0.42	575	115	1400	1400	25 (1.6%) 20 (1.3%)	291	12

Information described herein is based on Interim Report SD94-04 "Evaluation of Non-Metallic Fiber Reinforced Concrete in PCC Pavements and Structures" prepared by Dr. V. Ramakrishnan, Sept 1995.

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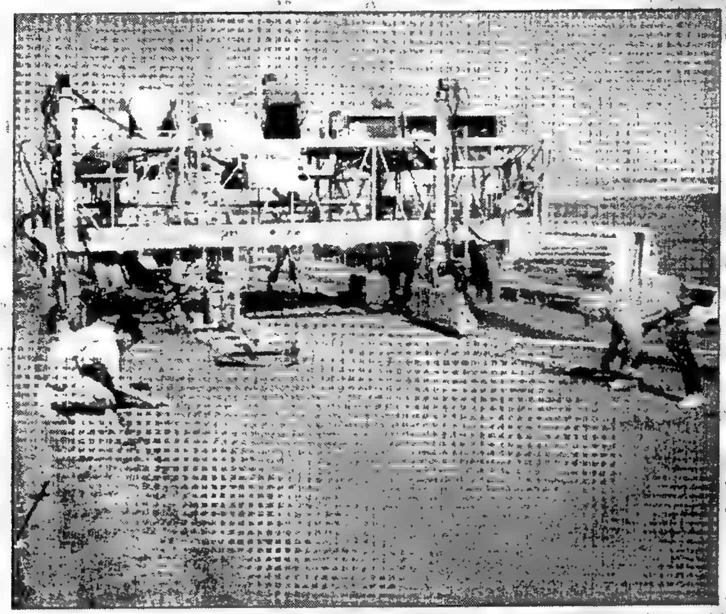
Polyolefin Fibers Case History

Whitetopping — US Hwy 14, Pierre, SD



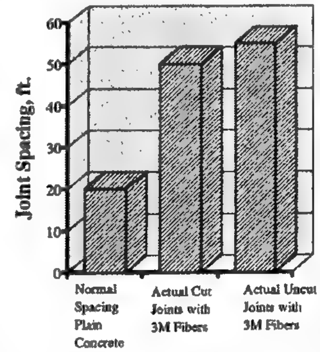
Compared to conventional whitetopping 3M FRC increased joint spacing plus this whitetopping is expected to have increased performance properties and pavement life.

1. Project Description

This project is located on US Hwy 14 West of Pierre, SD near mile marker 222.

- ***Owner:*** South Dakota Dept. of Transportation (SDDOT)
- ***Concrete Supplier:*** Morris Redi-Mix
- ***Contractor:*** Anderson Contractors, Inc.
- ***Designer:*** SD DOT and Dr. Ramakrishnan, South Dakota School of Mines and Technology
- ***Placement Date:*** July/August 1996
- ***Features & Requirements:*** Asphalt pavements, like all constructed pavements, deteriorate and asphalt overlays have several problems. It is necessary to validate whitetopping as an alternative to asphalt overlays. This larger full scale construction was designed to help answer questions pertaining to using 3M FRC such as: constructability, economic impact, whitetopping thickness, joint spacing, behavior of jointed and unjointed overlays and economic considerations, especially life cycle costs.
- ***Why 3M Fibers Were Used:*** This larger full scale whitetopping used 3M fibers because of favorable results on previous shorter whitetopping sections (see 3M Case History detailing the US Hwy 83/I90 whitetopping). After two years that whitetopping has performed well even tough the underlying asphalt was severely cracked in places. 3M fibers are an easy-to-use, cost effective, high performance fiber system that can increase the ductility, toughness, and crack resistance of whitetoppings. As a result, whitetoppings using 3M fibers are expected to last longer than conventional whitetoppings and asphalt overlays.

Joint Spacing Comparison



Uncut joints means distance between naturally occurring cracks in uncut sections and is generally expected to indicate acceptable joint spacing.

2. Job Execution

- ***Preparation:*** Traditional cold milling was used to remove existing asphalt. The asphalt was milled to a depth that removed most of the rutting.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was added to the mix at 25 pcy (1.66% by volume) at an off-site batch plant. The fibers were added to the concrete from a platform on a fork truck that was lifted to the back of the concrete truck. The 3M FRC was mixed five minutes.
- ***Concrete Placement:*** The fibers were used as an alternative to wire mesh, rebar and low volume fiber additions. The mixed concrete was delivered to the site in readymix trucks. The concrete was placed using a paver and a stringline. No special equipment was required to place the 3M FRC. Because the fatigue strength of the 3M FRC is significantly greater than non-FRC, this project was able to evaluate thin sections of 2 1/2 inch and 3 1/2 inch thickness (currently there is no concensus on whitetopping thickness design). The surface was finished with a 10 foot straightedge, a bull float, carpet drag and tining. A typical curing compound was used. Joints were cut after sufficient curing.
- ***Whitetopping Size:*** 2160 feet long and 24 feet wide using 444 cu. yds. of 3M FRC.
- ***Observations:*** The fibers were uniformly distributed throughout the mix. Each fiber was completely coated with cement paste. Surface preparation, mixing, placing and finishing of 3M FRC whitetopping required about the same quantity of time as working with conventional concrete and it paved similar to conventional concrete.

Whitetopping Section Design

Section	Length (ft)	Type	Thickness (in)	Joint Spacing (ft)	Fiber Concrete Volume (cu. yd.)
A	500	Fiber 25 pcy	2.5	50	93
B	500	Fiber 25 pcy	3.5	50	129
C	160	Plain	12	20	
D	500	Fiber 25 pcy	3.5	No cut joints	129
E	500	Fiber 25 pcy	2.5	No cut joints	93
Asphalt overlay	500	Control			NA

Note: Section C was full depth plain concrete to allow for weight measurements of passing traffic to determine load on the whitetopping sections.

3. Results/Conclusions

The addition of 3M fibers has been shown by SD DOT on previous concrete studies to increase load capacity, toughness, ductility, fatigue and crack resistance, as well as anticipated longer life and reduced maintenance.

Experience on other projects has shown that concrete reinforced with 3M fibers permitted longer joint spacings and less sawing with anticipated reduced maintenance costs. One of the goals of this project was to show how the joint spacing could be increased. On the unjointed section, the cracks were observed to average 55 feet on-center, which is similar to the 50 foot cut joints on other sections. Longer joint spacing reduces the likelihood of damage from water since there would be fewer joints. Fewer joints also means less sawing and potential reduced future maintenance.

Researchers found no adjacent lateral cracks from one slab to the other. None of the cracks found were reflected from the asphalt, indicating it is not necessary to fill cracks in the asphalt.

The 2 1/2 inch thickness can probably be cost justified on a first cost basis. But, when potential reduced maintenance costs due to increased joint spacing is considered, using 3M fibers on this project is expected to further increase cost savings.

The 3M FRC whitetopping is expected to save money and increase crack resistance, toughness, fatigue resistance, load capacity and expected pavement life.

Concrete Mixes and Proportions

Mixture Type	Fiber Diameter	Fiber Length	WC (W/(C+FA)) Ratio	Cement (Type II) lbs/cu. yd.	Fly Ash lbs./cu. yd.	Coarse Aggregate lbs./cu. yd.	Fine Aggregate lbs./cu. yd.	Fibers lbs./cu. yd. (vol. %)	Water lbs./cu. yd.	High Range Water Reducer
3M FRC	0.25 in.	2 in.	0.45 max.	575	115	1400	1400	25 (1.6%)	291	As needed

Slump was 1 to 4.5 inches.

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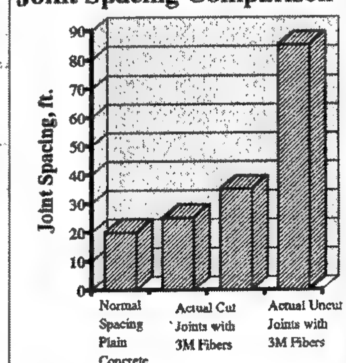
Polyolefin Fibers Case History

Pavement — US Hwy 83, Onida, SD

3M FRC concrete showed good constructability, beneficial economics and increased joint spacing that is expected to lead to future cost savings.

Joint Spacing Comparison



Uncut joints means distance between natually occuring cracks in uncut sections and is generally expected to indicate acceptable joint spacing.

1. Project Description

This project is located in Onida, SD which is Northeast of Pierre on US Hwy 83 North from the East junction with US Hwy 14.

- ***Owner:*** South Dakota Dept. of Transportation (SDDOT)
- ***Concrete Supplier:*** Stanley J. Johnsen Concrete Contractor.
- ***Designer:*** SD DOT and Dr. Ramakrishnan, South Dakota School of Mines and Technology
- ***Placement Date:*** August 1996
- ***Features & Requirements:*** Due to a decaying infrastructure and tightening budget constraints, SD DOT transportation engineers are being challenged to replace existing PCC pavements economically with an increase in performance. Also, this larger full scale construction was designed to help answer questions pertaining to using 3M FRC such as: constructability, economic impact, pavement thickness, joint spacing, effectiveness of load transfer across joints and random cracks, and the behavior of jointed and unjointed slabs.
- ***Why 3M Fibers Were Used:*** This larger full depth pavement placement used 3M fibers because of favorable results on previous smaller placements (see 3M Case Histories detailing: Sheridan Lake Road Pavement and US Hwy 83/190 bridge deck overlay, white-topping and jersey barrier). 3M fibers are an easy-to-use, cost effective, high performance fiber system that can increase the ductility, toughness, and crack resistance of concrete. As a result concrete using 3M fibers is expected to last longer than conventional concrete.

2. Job Execution

- ***Preparation:*** Traditional preparation methods were not changed on this project due to the use of 3M fibers.

- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was added to the mix at 25 lbs./cu.yd. (1.66% by volume) using a portable batch plant. Fibers were conveyed to the top of the of the batch plant, dumped into a chute, sprayed with water, dropped into the weigh hopper, then the rock was added on top of the fiber bundles. The operator opened the clam shell dropping fiber bundles and rock onto the conveyer which carried it to the mixer. The 3M FRC was mixed for 80 to 90 seconds, then discharged into dump trucks and driven to the job site.
- ***Concrete Placement:*** the trucks dumped the concrete into the spreader. Just as with conventional concrete the spreader placed the concrete and the paving machine smoothed it and removed the tears, gaps and voids left by the spreader.
- ***Pavement Size:*** 2,700 cu. yds. of 3M FRC was placed to form approximately 4,000 feet (1.2 km, 0.7 miles) of 3M FRC pavement two lanes wide (28 feet) with an additional control section of 1,000 feet (0.3 km. 0.2 miles).
- ***Observations:*** The fibers were uniformly distributed throughout the mix. Each fiber was completely coated with cement paste. Surface preparation, mixing, placing and finishing of 3M FRC pavement required about the same quantity of time as working with conventional concrete. According to the contractor, there was no noticeable difference in time spent paving between the non-fiber and fiber concrete.

Pavement Section Design

Section	Length (ft)	Thickness (in)	Joint Spacing (ft)	Dowels	Fiber
A	1000	8	20	YES	NO
B	250	6.5	25	NO	YES
C	245	6.5	35	NO	YES
D	500	8	25	YES	YES
E	490	8	35	YES	YES
F	500	8	25	NO	YES
G	490	8	35	NO	YES
H	1290	8	See Note 1	NO	YES

1. Upon curing uncut joint (cracks) occurred at approximately 85 feet center-to-center. This section was intentionally uncut so as to determine what the potential maximum joint spacing could be.

3. Results/Conclusions

The addition of 3M fibers has been shown by SD DOT on previous pavement studies to increase load capacity, toughness, ductility, fatigue and crack resistance, as well as anticipated longer life and reduced maintenance.

Experience on other projects has shown that concrete reinforced with 3M fibers permitted longer joint spacings and less sawing with anticipated reduced maintenance costs. One of the goals of this project was to show how the joint spacing could be increased. On the unjointed section, the cracks were observed to average 85 feet on-center - compared with 20 foot joints on-center in traditional concrete pavement. Therefore, based on limited previous experience an 80 foot joint spacing could have been used. If this longer joint spacing were used, the potential maintenance cost reduction could be one-fourth normal costs over the life of the surface. Also, longer joint spacing reduces the likelihood of damage from water since there would be fewer joints.

When potential reduced maintenance cost due to increased joint spacing is considered, using 3M fibers on this project is expected to save money. It is also expected this project will show increased performance similar to previous projects.

Concrete Mixes and Proportions

Mixture Type	Fiber Diameter	Fiber Length	WC (W/(C+FA)) Ratio	Cement (Type II) lbs/cu. yd.	Fly Ash lbs./cu. yd.	Coarse Aggregate lbs./cu. yd.	Fine Aggregate lbs./cu. yd.	Fibers lbs./cu. yd. (vol. %)	Water lbs./cu. yd.	Air Content %
3M FRC	0.25 in.	2 in.	0.52 (0.42)	510	112	1417	1417	25 (1.6%)	264	6.5 +/- 1.5

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Polyolefin Fibers Case History

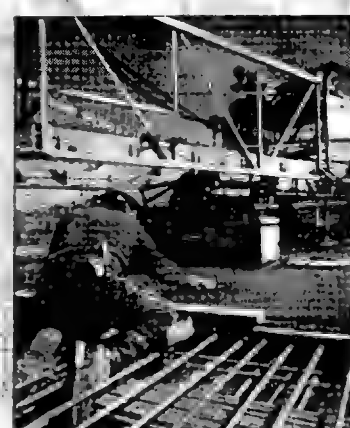
Bridge Deck Replacement — US85/I-90, Spearfish, SD

Using 3M fibers significantly reduced cracking, and crack length and width compared to similar bridges constructed without 3M fibers, so this bridge is expected to last longer.

1. Project Description

This project is a bridge deck replacement of the US Hwy 85 bridge over Interstate 90 at exit 10 near Spearfish, SD. This project also included replacement of the jersey barrier.

- ***Owner:*** South Dakota Dept. of Transportation (SDDOT)
- ***Concrete Supplier:*** Birdsall Sand and Gravel
- ***Contractor:*** Heavy Constructors Inc.
- ***Designer:*** SD DOT and Dr. Ramakrishnan, South Dakota School of Mines and Technology
- ***Placement Date:*** September/ October 1995
- ***Features & Requirements:*** Bridge cracking is a national concern. Cracks reduce the life expectancy of structures due to ingress of water and water borne chemicals that deteriorate the structure's materials. A major concern in this project was reducing the occurrence of cracks and reducing crack width and length of those that did occur.
- ***Why 3M Fibers Were Used:*** This larger full depth bridge deck replacement and jersey barrier project used 3M fibers because of favorable results on previous smaller placements (see 3M Case Histories detailing: US Hwy 83/190 bridge deck overlay, white-topping and jersey barrier). 3M fibers are an easy-to-use, cost effective, high performance fiber system that can increase the ductility, toughness, and crack resistance of concrete. As a result, concrete using 3M fibers is expected to last longer than conventional concrete. 3M fibers were especially considered due to the significant reduction in cracking and reduction in crack length and width on previous projects.



2. Job Execution

- ***Preparation:*** Traditional preparation methods were not changed on this project due to the use of 3M fibers. Typical epoxy coated rebar was used as standard bridge reinforcement.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was added to the mix at 25 lbs./cu.yd. (1.66% by volume) at a batch plant. Fiber bundles were loaded from their boxes into a 1/2 cu. yd. concrete bucket, suspended from a boom truck and then added to the concrete truck while it was turning at mixing speed. The 3M FRC was mixed for approximately five minutes.
- ***Concrete Placement:*** At the site the concrete was discharged into the pump and pumped up to the bridge. Because of the quantity of reinforcement required on the deck the, 3M FRC was consolidated using a poker vibrator. A bridge paving machine finished the concrete. The surface was bull floated, broomed and tined.
- ***Bridge Deck Size:*** 40 feet wide by 340 feet long (13,600 sq. ft.) using 424.9 cu. yds. of 3M FRC.
- ***Observations:*** The fibers were uniformly distributed throughout the mix. Each fiber was completely coated with cement paste. The contractor found during both a test placement and the actual placement that surface preparation, mixing, placing and finishing of 3M FRC pavement required about the same quantity of time as working with conventional concrete and that 3M FRC behaved in the same manner as conventional concrete.

3. Results/Conclusions

The addition of 3M fibers has been shown by SD DOT on previous concrete studies to increase load capacity, toughness, ductility, fatigue and crack resistance, as well as anticipated longer life and reduced maintenance.

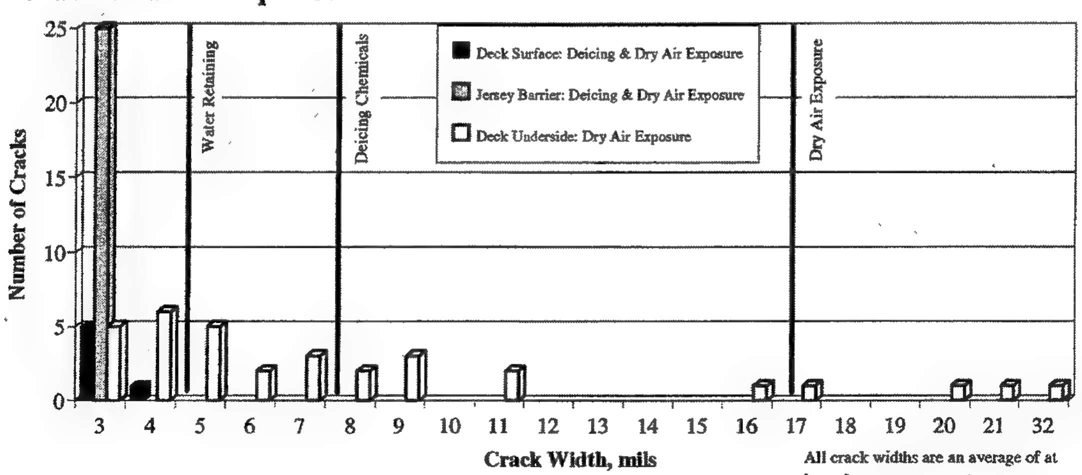
Experience on other projects has shown that cracks have been reduced in concrete reinforced with 3M fibers. One of the goals of this project was to reduce the occurrence of cracks and crack widths and lengths of those that did occur. The ACI tolerable cracks widths are: 4 mils for watertight structures, 7 mils for de-icing chemicals, and 16 mils for air.

After nine months this bridge was analyzed for cracks. The results are impressive. On the top of the bridge deck, where the exposure is to air and de-icing chemicals, no significant cracks were found. Six hairline cracks were observed on the untined edge near the barrier. One crack was 4 mils wide. The remaining five were 3 mils wide or less. These six water-tight cracks were on average 12 inches long. On the 680 feet of jersey barrier, where exposure conditions were also air and de-icing chemicals, 25 hairline cracks were observed. All were 3 mils wide or less. On the underside of the bridge deck, only four of 32 cracks exceeded the tolerable crack width for the dry air exposure condition. The largest of these four was about 32 mils wide and approximately 6 ft. long.

This research project clearly demonstrated that a bridge deck can be built with 3M FRC using standard equipment and procedures. Using 3M fibers also significantly reduced crack widths and lengths, and this bridge deck has fewer cracks than comparable bridges constructed of non-fiber concrete.

As a result, the use of 3M fibers is expected to add years to the life of this bridge deck.

Crack Width Camparison



All crack widths are an average of at least three measurements.

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Polyolefin Fibers Case History

Pavement — Sheridan Lake Road, SD

Compared to the best available steel fibers, 3M fibers provided: less chance for mixing, finishing and other construction problems; 30% pavement depth reduction and enhanced performance with a potential for longer life and less maintenance.

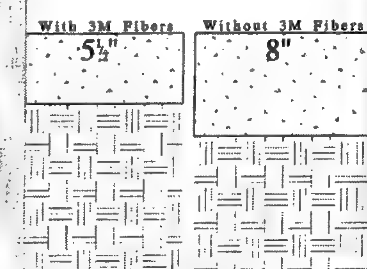
1. Project Description

- ***Owner:*** South Dakota Dept of Transportation (SDDOT)
- ***Contractor:*** Heavy Constructors, Inc.
- ***Designer:*** SDDOT and Dr. Ramakrishnan, South Dakota School of Mines and Technology
- ***Placement Date:*** June/July '94.
- ***Features & Requirements:*** Pavements need to be replaced or rehabilitated with increased performance and life cycle economy. This project evaluated performance of 3M fibers compared to steel fibers and plain concrete to determine if 3M fibers are a viable alternative for future projects.
- ***Why 3M Fibers Were Used:*** The advantages of a non-metallic material combined with the structural property improvements and potential for thinner slab sections and reduced life cycle cost.

2. Job Execution

- ***Preparation:*** Excavation was reduced due to reduced slab thickness.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was added at the concrete batching facility. See back page for mix information.
- ***Concrete Placement:*** The concrete was placed using a slip form paver machine. With re-tempering in the field or super plasticizer added at the plant the fiber reinforced concrete placed and finished with no problems in mixing, handling or finishing.
- ***Slab Size:*** 75' long by 4—12' lanes wide and 5½" thick with 15' sections on each end as transitions to and from the thicker slab depth.
- ***Observations:*** Concrete using 3M fibers placed, consolidated and finished satisfactorily compared to steel FRC and plain concrete.

Slab Depth Comparison



3. Results/Conclusions

Based on observations made in this and other field applications, it was learned that the new 3M polyolefin fiber system had combined the structural benefits of steel fibers and the material benefits of synthetics.

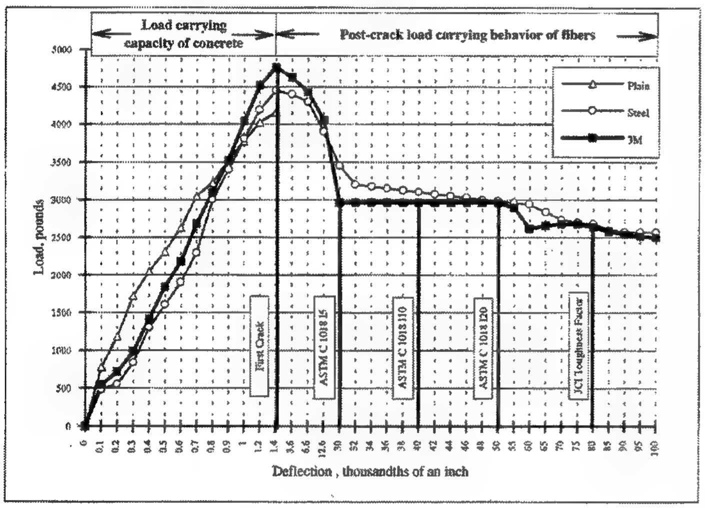
It is possible to incorporate the [3M] polyolefin fibers in concrete at 25 lbs/cu. yd. without causing any balling, clogging and segregation. The advantages of adding polyolefin fibers compared to the best available steel fibers were: 1. Four times greater number of fibers are added in concrete ensuring more uniform distribution and consistent results.
2. Less chance for balling, segregation, bleeding or causing any other construction problems during mixing, placing, consolidation, finishing and tining operations.
3. Fibers are non-corrosive, non-hazardous, and non-magnetic. They do not protrude from the surface; if they do, they could be easily burned off.

The 25 lbs/cu. yd. of 3M fibers were added without making any mix proportion adjustments.

Required workability and finishability could be achieved.

The addition of [3M] polyolefin fibers at 20 or 25 lbs/cu. yd. enhanced the structural properties of concrete. There was a slight increase in flexural strength, and a considerable increase in toughness, impact, fatigue, endurance limit and post crack load carrying capacity. This improvement was the same or in some cases (such as impact) better than the enhancement that could be achieved with the addition of 66 lbs./cu. yd of the best available steel fiber in the market.

This feasibility study has confirmed that 3M FRC with 25 lbs./cu. yd. could be used in the construction of full depth pavements with 30 percent reduction in the thickness and other added benefits. 3M FRC pavements would enhance the performance and structural efficiency with a potential for longer life with less maintenance. 3M FRC pavements could be used in all highways, urban, rural, or interstate highways either with high density or low density traffic.



Summary of Test Results:

- **Toughness** (ASTM and JCI Standards) — Results based on the load/deflection curve shows elastic/plastic behavior of 3M fiber reinforced concrete (FRC) and post-crack load carrying capacity similar to steel FRC.
- **Flexural Strength** — 3M FRC increased the ability of concrete to withstand loads in flexure by approximately 13%.
- **Fatigue Strength/Endurance** — 3M FRC was able to endure two million fatigue cycles at a load similar to steel FRC, ~ 30% greater than plain concrete.
- **Impact Strength** — 3M FRC was over two times greater than steel FRC for resistance to failure due to impact and almost 14 times greater than plain concrete.
- **Compressive Strength** — 3M fibers do not significantly affect compressive strength.

Concrete Mixes and Proportions

Mixture Type	Fiber Diameter	Fiber Length	Water/ Cement Ratio	Cement lbs/cu. yd.	Fly Ash lbs/ cu. yd.	Coarse Aggregate lbs./cu. yd.	Fine Aggregate lbs./cu. yd.	Fibers lbs. cu. yd. (vol. %)	Water lbs./cu. yd.	AEA oz./cu. yd.
Plain Concrete	NA	NA	0.47	519	114	1770	1270	0	242	15.0
Steel FRC	0.8 mm	59 mm	0.50	525	113	1634	1331	66 (0.5%)	263	11.5
3M FRC	0.63 mm	50 mm	0.50	525	113	1634	1331	25 (1.6%)	263	11.5

Information contained here is based on Interim Report SD94-04 "Evaluation of Non-Metallic Fiber Reinforced Concrete in PCC Pavements and Structures" prepared by Dr. V. Ramakrishnan, Sept 1995.

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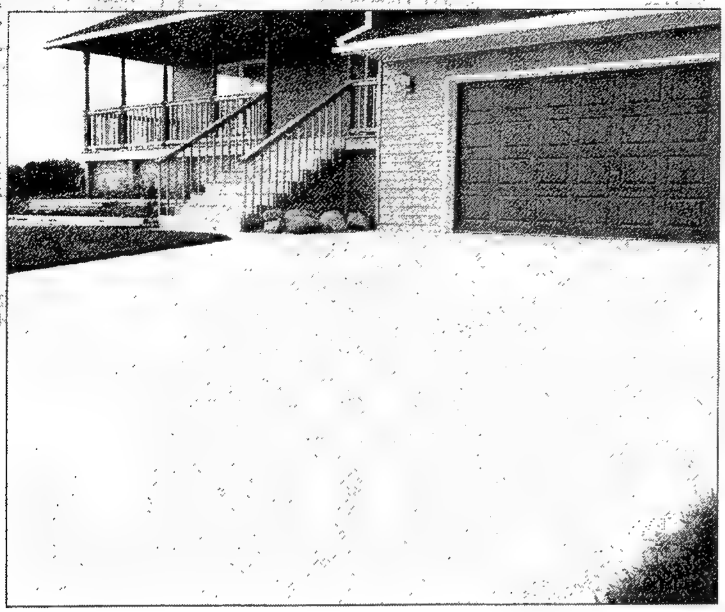
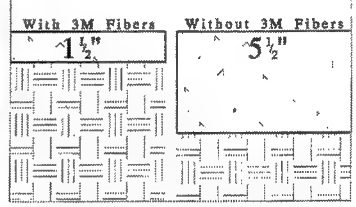
Residential Driveway Test — Hugo, MN



"This is just what I wanted and it works great!"

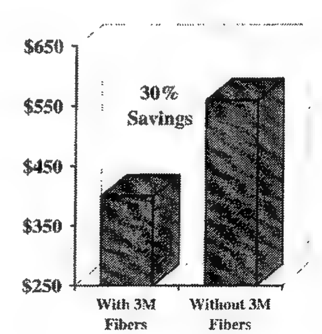
Owner

Slab Depth Comparison



3M fibers used for this project allowed a much thinner section than typical Non-FRC driveway slab thickness.

Cost Comparison



1. Project Description

- ***Owner:*** Carl Reimer. Hugo, MN
- ***Concrete Supplier:*** Wyatt Concrete, Minneapolis, MN
- ***Placement Date:*** October 1993.
- ***Features & Requirements:*** Slab thickness was reduced to 1½" thick instead of typical 5" thick to keep cost to the one truckload limit. Since this was a test, the placement was done in one monolithic pour to determine how 3M fibers would control plastic shrinkage cracking and prevent differential settlement at cracks that may develop.
- ***Why 3M Fibers Were Used:*** Potential for reduced slab depth due to improved concrete material performance characteristics. crack width size control and material properties of polyolefin.

2. Job Execution

- ***Preparation:*** Concrete was placed on level. compacted, crushed rock.
- ***Concrete Mix and Fibers:*** Standard driveway mix using 60% coarse aggregate with 15 mil, 2" 3M fiber type at 15 lbs/cu.yd..
- ***Placement size:*** 24' by 45' with no saw cuts or tooled joints.
- ***Observations:*** There was good fiber distribution and no balling of fibers.

3. Results/Conclusions

There was no differential settlement of the slab. Crack widths were acceptable (about 13 mils or less). 3M fibers reduced overall material costs and have performed well under severe Minnesota winter conditions.

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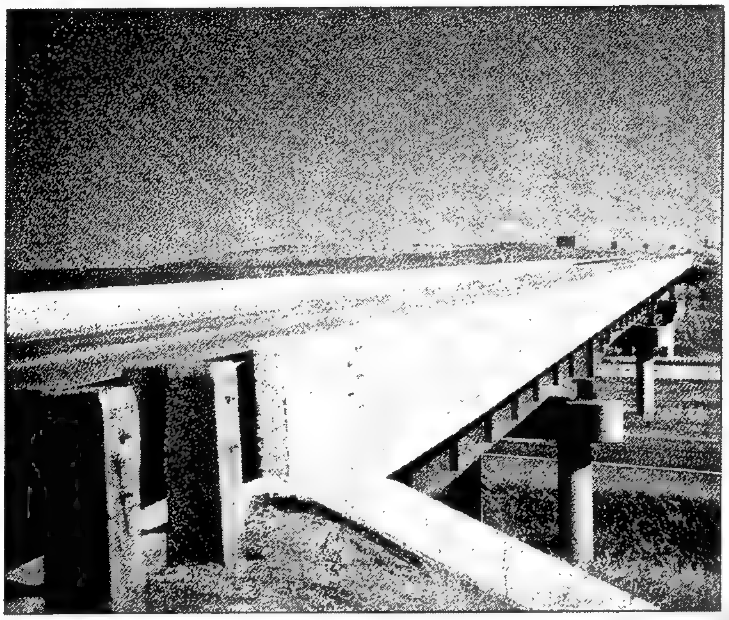
Jersey Barrier — US Hwy 83, SD



3M Fibers reduced crack widths and increased impact strength, toughness, durability and life span thereby reducing or avoiding future repair cost.

1. Project Description

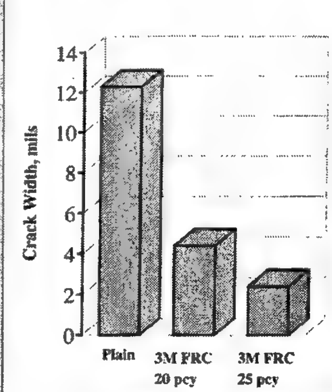
The location of this project was on the US hwy 83 structure over I-90 south of Pierre, SD (structure number 43-026-195) mile marker 212

- ***Owner:*** South Dakota Dept of Transportation (SDDOT)
- ***Concrete Supplier:*** Ready Mix Presho Plant
- ***Designer:*** SDDOT and Dr. Ramakrishnan, South Dakota School of Mines and Technology
- ***Placement Date:*** August 1994
- ***Features & Requirements:*** SD DOT requires Jersey Barriers constructed, replaced or rehabilitated with increased performance (especially impact resistance) and life cycle economy. 3M fibers were compared to plain concrete to determine if they are a viable alternative for future projects.
- ***Why 3M Fibers Were Used:*** The advantages of a non-metallic material combined with the structural property improvements and potential reduced crack width and increased life.

2. Job Execution

- ***Preparation:*** No change in typical formwork and preparation was required.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was added to the ready mix truck at the batch plant. See back page for mix information.
- ***Concrete Placement:*** Because of slump loss and rebar extra effort was required for consolidation into the forms.
- ***Barrier Size:*** The West barrier (~372') was placed using 3M fibers. The North half used 20 lbs./cu. yd. and the South half used 25 lbs./cu. yd. The East barrier had no fibers
- ***Observations:*** Although extra effort was required to place and consolidate the concrete, when one side form was removed it was noticed that the concrete had been well

Average Crack Width Comparison



consolidated and there were no honeycombs. There was a significant difference between cracks in plain concrete and cracks in 3M FRC.

3M FRC had 57% more cracks than the plain concrete. However, the cracks in the 3M FRC were on average 3.5 times smaller than the cracks in the plain concrete. Plus, the fibers in the concrete will help prevent cracks from becoming larger. The larger cracks in the plain concrete will cause future deterioration problems with the rebar. See charts on front page and below for comparison.

3. Results/Conclusions

The 20 and 25 lbs/cu. yd. of 3M fibers were added without making any mix proportion adjustments. The addition of [3M] polyolefin fibers at 20 or 25 lbs/cu. yd. enhanced the structural properties of the concrete.

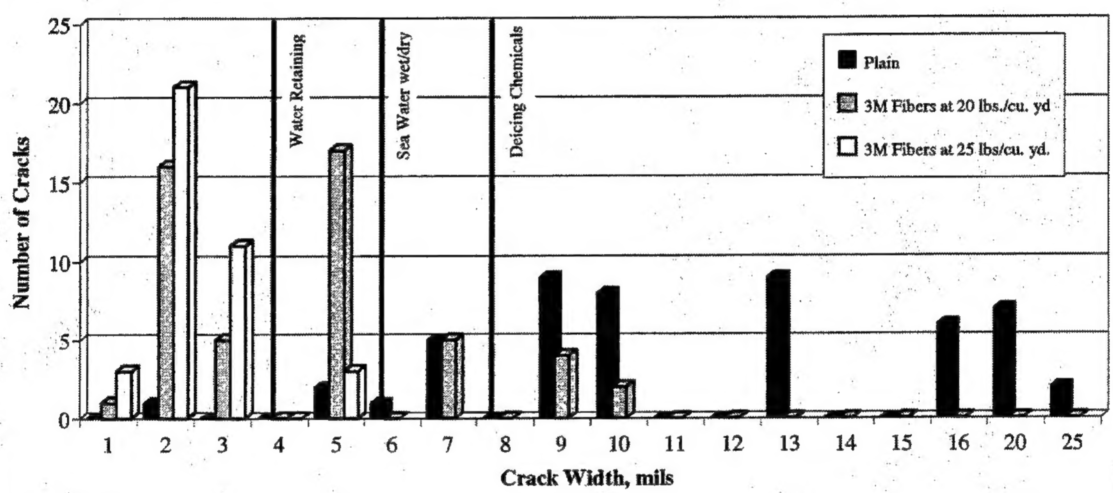
As anticipated, the addition of 3M fibers greatly increased the toughness of concrete. The ASTM toughness indices I5, I10 and I20 are approximately 4, 8 and 15 times higher than that of plain concrete.

The histograms of the crack widths for plain concrete and 3M FRC show the benefits of the fibers and using the higher fiber dosage.

The cracks in plain concrete and 3M FRC were compared to the ACI 224 tolerable crack width of 4 mils for water retaining, 6 mils for sea water wet/dry cycles and 7 mils for deicing chemicals. If cracks are narrower than these widths, the potential for reinforcement corrosion due to moisture penetration is reduced or eliminated and concrete is more durable.

93% of cracks in 3M FRC were 7 mils or smaller while only 15% of plain concrete cracks were 7 mils or smaller. This means that most cracks (85%) in plain concrete were large enough to allow deicing chemicals to penetrate into the concrete. Most cracks in 3M FRC were small enough to meet ACI standards for deicing chemicals exposure and even for water retaining structures. See charts below for more information.

This reduced crack width helps extend the durable life of the concrete and significantly improves the impact resistance which is the main purpose of the Jersey barrier.



Concrete Mixes and Proportions

Mixture Type	Fiber Diameter	Fiber Length	Water/ Cement Ratio	Cement lbs/cu. yd.	Coarse Aggregate lbs./cu. yd.	Fine Aggregate lbs./cu. yd.	Fibers lbs. cu. yd. (vol. %)	Water lbs./cu. yd.	AEA oz./cu. yd.
Plain Concrete	NA	NA	0.31	670	1728	1189	none	272	12
3M FRC	0.63 mm	50 mm	0.31	670	1728	1189	25 (1.6%) 20 (1.3%)	272	10

Information described herein is based on Interim Report SD94-04 "Evaluation of Non-Metallic Fiber Reinforced Concrete in PCC Pavements and Structures" prepared by Dr. V. Ramakrishnan. Sept 1995.

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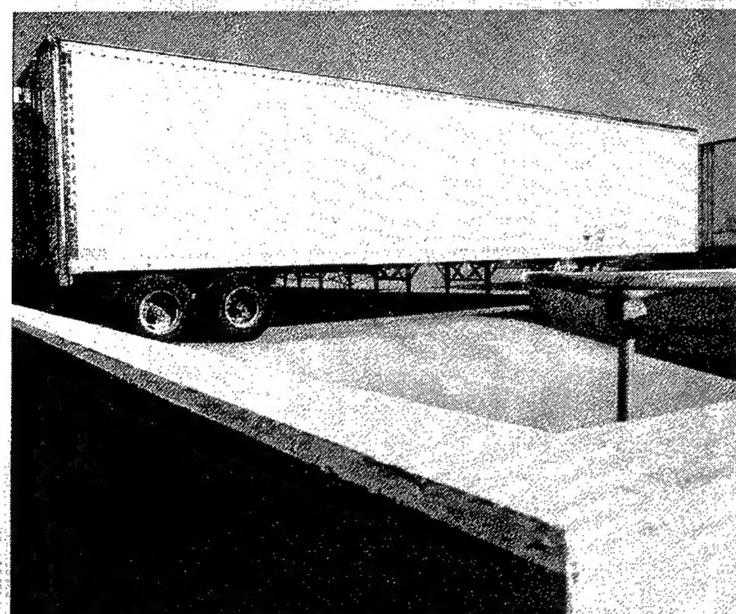
Polyolefin Fibers Case History

Chemical Waste Containment — Cottage Grove, MN



"Using 3M fibers saved 23% compared to the cost of using rebar and 3M fibers provided life cycle benefits and required performance enhancements"

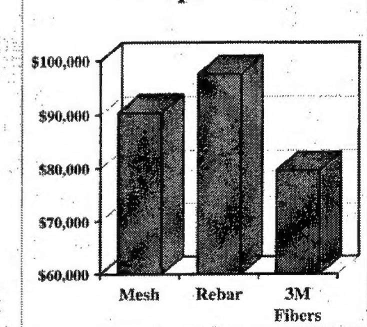
1. Project Description

- ***Owner:*** 3M
- ***Concrete Supplier:*** Cemstone Products Co., Hastings, MN
- ***Designer:*** Toltz King Duvall Anderson & Associates, St. Paul, MN
- ***Placement Date:*** July 1995
- ***Features & Requirements:*** Low cost and leak free reliability were requried for this temporary storage facility for chemical waste from the 3M Chemolite plant. The area is a sloped slab-on-grade with truck access on one side and low barrier walls on three sides.
- ***Why 3M Fibers Were Used:*** Compared to mesh and rebar, 3M fibers were the least expensive on a first cost basis, provided life cycle cost reductions and performance improvements (such as improved toughness and crack control) needed for leak free containment.

2. Job Execution

- ***Preparation:*** Excavation was reduced, and preparation simpler since rebar or mesh placement was not needed.
- ***Concrete Mix and Fibers:*** 3M fiber 50/63 was added at the concrete batching facility via conveyor. See back page for mix.
- ***Concrete Placement:*** The concrete was placed using a vibrating screed. The fiber reinforced concrete placed and finished with no problems in mixing, handling or finishing.
- ***Slab Size:*** 130' by 230' placed in strips of 25' by 130'. Joints were sawcut at 25' intervals.
- ***Observations:*** If conventional reinforcement had been used, worker safety, reinforcing placement and access for placing concrete would have been additional cost burdens.

Slab Cost Comparison



3. Results/Conclusions

The slab is performing as expected and needed for containment. 3M fibers reduced overall material costs.

Slab Cost Comparison

Reinforcement	Mesh		Rebar		3M fibers	
Thickness	9 inches		6 inches		5.5 inches	
Joint space	23 feet		18 feet		25 feet	
Concrete (M) $75/cy	$	62,292	$	41,528	$	38,067
Excavation (LE) $4.40 cy p.38	$	3,700	$	2,400	$	2,200
#4 Rebar 12" C.C. E.W. (LM) $0.61/lb. p. 125		NA	$	24,467		NA
Epoxy coat (M) $0.23/lb. p. 125		NA	$	9,188		NA
Handling (LE) $0.03/lb. p. 125		NA	$	1,298		NA
High chair (M) $0.38 ea/sy p. 123		NA	$	1,262		NA
Mesh (LM) $29.50/csf p. 126	$	8,821		NA		NA
3M Polyolefin fibers (M) $50.50/cy		NA		NA	$	25,505
Handling fibers (L) $5/cy		NA		NA	$	2.538
Sawcuts T/4 (LME) $1.18/lf/in D p. 27	$	6,160	$	5,204	$	3,180
Backer rod (LM) $0.71/lf p. 178	$	1,636	$	2,073	$	1,382
Sealants (LM) $2/lf p. 179	$	4,640	$	5,880	$	3,920
Dowels 12" C.C. (LM) $2.71 p. 125	$	3,171	$	4,228	$	2,818
Total Cost	**$**	**90,420**	**$**	**97,528**	**$**	**79,610**
Percent over 3M fiber cost		**+14%**		**+23%**		**NA**
Difference between 3M fibers Cost	**$**	**10,810**	**$**	**17,918**		**NA**

Note: L=Labor, M=Materials, E=Equipment. When a page number is cited above it is the source in "Means Site Work & Landscape Cost Data 1995."

Mix Design

Item	Type/Units	Quantity
Cement	ASTM C 150 Type I	564 lbs.
Fly Ash	ASTM 618	96 lbs.
Sand	ASTM C 33	1417 lbs.
Gravel 3/4"	ASTM C 33/#67	1357 lbs.
Water		330 lbs. (39.5 U.S. gal.)
Total Air		6% +/- 1%
Fiber	3M fiber 50/63	25 lbs.
WRR-Daratard 17	ASTM C 494 Type D	19.80 oz.
AEA	ASTM C 260	5.0 oz.
Water/Cement Ratio	lbs./lb.	0.50
Slump	inches	4.00
Concrete unit weight	pounds per cubic foot	139.4

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13. ABSTRACT *(Maximum 200 words)*
This report documents the results from an investigation of a new polymer fiber and unique delivery system for charging fibers into concrete mixtures. The straight Polyolefin fibers are available in two sizes: (1) 0.63 mm in diameter and 50 mm long, and (2) 0.38 mm in diameter and 25 mm long. Each of the two sizes of fibers is packaged in bundles approximately 50 mm in diameter. Each bundle is encased with paper tape bound with a water-soluble glue. The fibers are charged into the concrete mixture in mass. Approximately 3 to 10 min of mixing time is necessary to uniformly distribute the fibers throughout the concrete mixture, depending upon the fiber content, consistency of the concrete mixture, and the type of mixer being used. Fresh and hardened properties were evaluated in mixtures containing up to 15 kg/m^3. The results indicate that concrete mixtures with the Polyolefin fibers can be produced having adequate workability and finishability if proportioned properly. Addition of the Polyolefin fibers does not significantly influence the compressive nor first-crack flexural strength, freezing-and-thawing resistance, drying shrinkage, nor the chloride permeability of concrete mixtures. However, the presence of the Polyolefin fibers does influence the post-crack behavior of concrete mixtures. Impact resistance and flexural toughness are improved as the fiber loading increases. A 6,100-m whitetopping demonstration project was constructed on a heavily traveled interstate in Mississippi. The whitetopping was 100 mm thick. Details of the specifications, construction, and early-time performance are given.

14. SUBJECT TERMS

Concrete	Flexural toughness	Polyolefin fibers
Concrete fibers	Impact resistance	Ultra-thin whitetopping
Fiber-reinforced concrete	Polymeric fibers	Whitetopping

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